STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

Geology of the Macdoel Quadrangle California

BULLETIN 151
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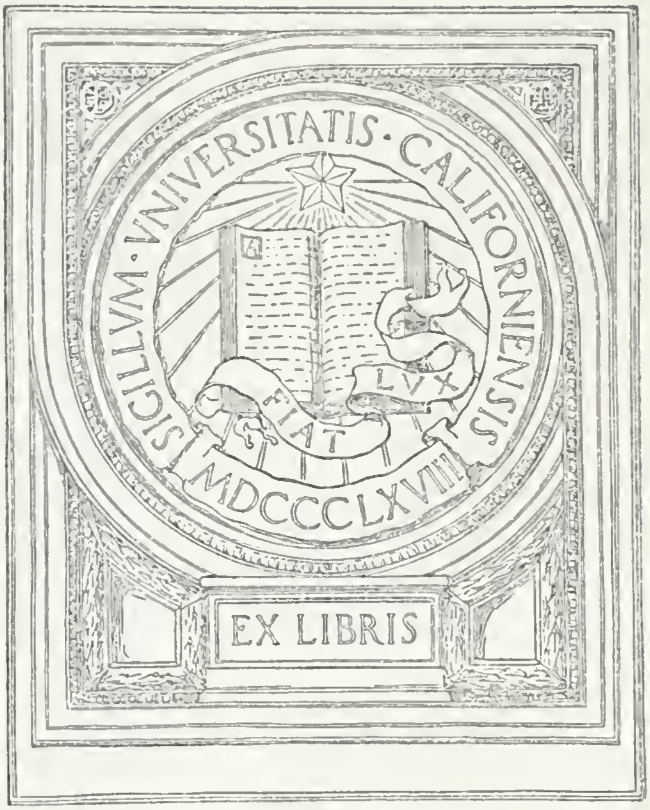
DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO



STATE OF CALIFORNIA
EARL WARREN, Governor
DEPARTMENT OF NATURAL RESOURCES
WARREN T. HANNUM, Director

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO
OLAF P. JENKINS, Chief

SAN FRANCISCO BULLETIN 151 NOVEMBER, 1949

GEOLOGY OF THE MACDOEL QUADRANGLE

By HOWEL WILLIAMS

and

Circular Soil Structures in Northeastern California

By PETER H. MASSON

LETTER OF TRANSMITTAL

To His Excellency
The Honorable Earl Warren
Governor of the State of California

Dear Sir:

I have the honor to transmit herewith Bulletin 151, *Geology of the Macdoel Quadrangle*, prepared under the direction of the Chief of the Division of Mines, Olaf P. Jenkins. The bulletin includes colored geologic and economic mineral maps and other pertinent data on a specific area in Siskiyou County, north of Mount Shasta and bounded by the Oregon border. The report describes deposits of building stone and crushed rock, diatomite, ornamental and gem stones, copper and molybdenum, and coal. It represents one of a series of such quadrangle reports which the Division of Mines is engaged in publishing. The field work was done on a cooperative basis with a faculty member of the University of California.

The author of this bulletin on the Macdoel quadrangle, Howel Williams, is head of the Department of Geological Sciences, University of California. As an eminent volcanologist, Dr. Williams' treatment of the geology is of particular interest, since this area is covered largely by volcanic rocks. Included with the report is an article on the origin of certain interesting rock rings concerning which frequent queries have been received by the Division of Mines. This article, *Circular Soil Structures in Northeastern California*, has been prepared through field investigations by a graduate student of the University of California, Peter H. Masson.

Respectfully submitted,

WARREN T. HANNUM, Director
Department of Natural Resources

July 1949

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GEOLOGY OF THE MACDOEL QUADRANGLE, CALIFORNIA

By Howel Williams *

OUTLINE OF REPORT

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* Chairman, Department of Geological Sciences, University of California, Berkeley, California. Manuscript submitted for publication January 1949.

ILLUSTRATIONS

ABSTRACT

The Macdoel quadrangle lies in Siskiyou County, adjoining the Oregon-California boundary on the north and lying close to U. S. Highway 99 on the west. It is mapped on a scale of 1:125,000.

Topographically it includes parts of Shasta Valley and Butte Valley, along with the intervening Cascade Range and a portion of the valley of the Klamath River.

The oldest rocks in the quadrangle are metacherts and quartzites, probably of Paleozoic age, which are intruded by quartz monzonite of Jurassic age. Similar rocks are widespread in the adjacent part of the Yreka quadrangle to the west, where they are accompanied by Jurassic (?) intrusions of serpentine and metadiabase. In that quadrangle these bedrocks are overlain with profound unconformity by marine, Upper Cretaceous (Chico) beds; these are not exposed in the Macdoel quadrangle but they underlie most of Shasta Valley and may extend beneath the Cascade Range.

Resting on the Cretaceous rocks are freshwater Eocene sediments belonging to the Umpqua formation which outcrop at the northern end and along the eastern edge of Shasta Valley.

With the exception of these small exposures of Eocene sediment and the still smaller outcrops of plutonic and metamorphic bedrocks previously mentioned, virtually the whole of the quadrangle is occupied by volcanic materials. These belong to two series, first the Western Cascade series, ranging in age from Eocene to Miocene, and second, the High Cascade series of Pliocene, Pleistocene, and Recent age. The older series covers most of the western half of the quadrangle, and is made up chiefly of andesitic lavas, with subordinate flows of basalt and dacite, beds of rhyolite tuff,

and a few domical protrusions of rhyolitic lava. No trace remains of the parent cones, but several necks mark the sites of the central vents of some of the vanished volvanoes. In brief, the topography in this belt of Western Cascade rocks is entirely erosional in origin.

At the close of the Miocene period this older series was gently tilted to the east and northeast, and was cut by faults that border long, narrow horsts trending slightly west of north. At the same time the ancestral Cascade Range was formed by regional uplift.

Subsequently, a north-trending chain of volcanoes was built along the crest of the range; their products form the High Cascade series. Here the topography is almost wholly constructional, and even the oldest cones retain much of their original shapes. During Pliocene and Pleistocene times, broad, flattish shield volcanoes were formed by quiet effusions of olivine basalt, while eruptions of andesite and perhaps of dacite built steeper cones alongside the shields. Among the andesitic cones produced mainly during the Pleistocene, the largest by far is Mount Shasta which adjoins the quadrangle on the south.

After the close of Pleistocene time, while the glaciers of Shasta were shrinking to their present size, many new volcanoes of andesite and basalt developed in the High Cascades, and copious floods of basaltic lava issued from fissures to inundate much of Butte and Shasta Valleys and the canyons of Butte and Alder Creeks, while other basaltic flows were discharged near Copco Dam, impounding the Klamath River to produce a large lake in which much diatomite was deposited.

Many of the Recent flows are not more than a few thousand years old, and perhaps the final eruption within the area took place within the present millennium.

Shasta Valley is a structural depression bordered on the east by a fault of great displacement, developed at the end of Miocene time. Butte Valley is also a downdropped block, but of much later origin, being surrounded by well-preserved fault scarps of late Pleistocene and Recent age.

Known economic mineral deposits are few. Copper and molybdenum are found in plutonic rocks on Yellow Butte, and a little coal has been mined in the Umpqua formation near Ager. Lavas and tuffs of the Western Cascade series, and basaltic cinders from younger volcanoes have been utilized for building materials and road metal. Opal and chalcedony have been collected for ornamental purposes.

INTRODUCTION

Location and Accessibility

The Macdoel quadrangle, scale 1:125,000, lies in Siskiyou County (fig. 1). Its northern boundary is the Oregon-California state line, and its southern boundary the parallel 41°30′ North. The other limits are the meridians 122° and 122°30′ West. The area thus enclosed covers approximately 940 square miles.

The small villages of Macdoel and Mount Hebron, close to the eastern edge of the quadrangle, are the principal settlements, but most of the population is scattered on farms in Butte and Shasta Valleys. Yreka, the county seat, lies a short distance to the west; Weed and Dorris, two important sawmill towns, lie a short distance to the south and east, respectively.

U. S. Highway 97, connecting Weed with Klamath Falls, cuts across the southeastern portion of the area, following close to the main line of the Southern Pacific Railroad. U. S. Highway 99, linking Weed with Yreka and Medford, lies a few miles to the west of the quadrangle. The Siskiyou branch of the Southern Pacific Railroad, after skirting the western edge of the area from Gazelle to Montague, enters the quadrangle at Snowdon, then passes through Ager to leave the area close to the northwestern corner (pl. 4).

Many secondary roads branch from the two main highways just mentioned, and a close network of oiled and gravelled roads facilitates access to the flat farming country. Two good roads, one from Hornbrook

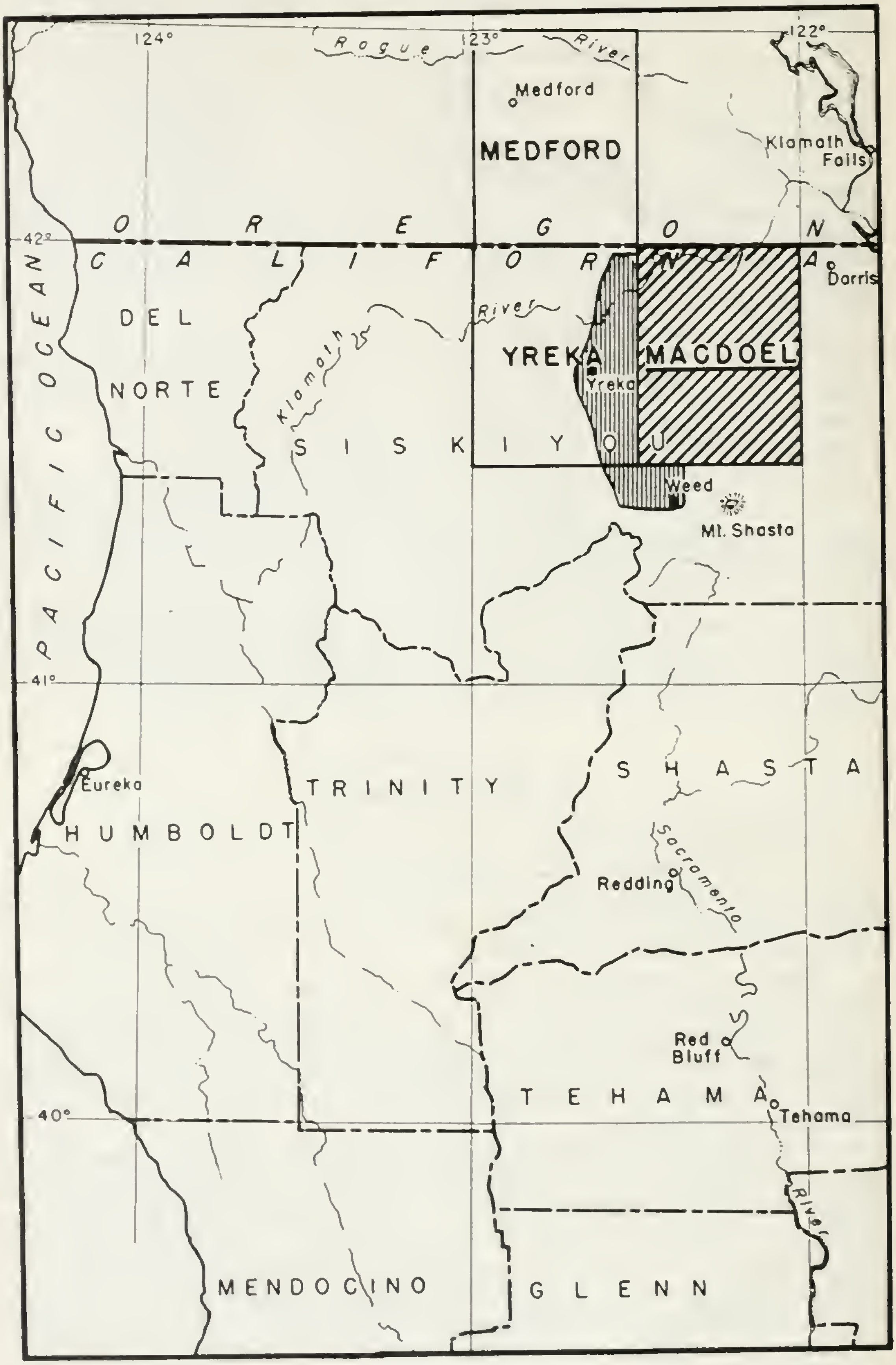

FIG. 1. Index map showing location of Macdoel quadrangle, and area covered by sketch map (plate 4) along Highway 99 from Weed to Hilt.

to the Copco Dam, and the other from Ager to Beswick, open up the valley of the Klamath River. The mountainous, central part of the region is crossed by the road between Montague and Mount Hebron, and much of it is traversed by Forest Service and logging roads.

Topography

The Macdoel quadrangle is divisible into four topographic units, namely, Shasta Valley, Butte Valley, the intervening Cascade Range, and the valley of the Klamath River.

Shasta Valley is an approximately oval basin, about 30 miles long in a north-south direction and 15 miles in greatest width, bordered on one side by the Siskiyou Mountains and on the other by the Cascade Range. Most of it lies between elevations of 2,400 and 2,800 feet. The eastern, flatter half is occupied by a vast flow of basaltic lava recently erupted from the flank of Mount Shasta; the western half consists of older volcanic rocks eroded into a myriad of hillocks that range from a few feet to 200 and rarely to 300 feet in height. Most of these hillocks are domical, some are conical, others are mesas and a few are long, hogback ridges. Together they form a strange landscape, deceptively like the products of recent volcanic activity. Between the hillocks lie many small ponds and marshes and the alluvial flats of slow, winding streams. Chief among these streams are Shasta River and its tributary Parks Creek which rise among the Siskiyou Mountains to the south. After feeding the Dwinnell Reservoir and meandering between the aforementioned hillocks, the Shasta River passes out of the quadrangle to continue its sluggish course for another 9 miles before plunging into the deep, rocky gorge through which it hurries to join the Klamath River. In the eastern half of Shasta Valley, owing to the porous nature of the lava floor, there are few streams, most of the subterranean drainage emptying into ponds and lush meadows in the lower, northern end.

On the opposite side of the Cascade Range lies Butte Valley, the bed of an ancient lake, a featureless plain covering more than 150 square miles, lying at an elevation of approximately 4,200 feet. Meiss Lake is all that now remains of the original body of water that formerly drained northward through Sam's Neck to the Klamath River. It has no outlet and its size varies greatly with the seasons. Abundant ground water is found all over the valley at shallow depths. The principal streams entering the basin are Butte Creek from the south and Prather Creek from the west; the former sinks underground soon after entering the basin, while the latter empties into Meiss Lake to augment the water discharged by adjacent springs. The valley itself is a huge, structural trough almost encircled by youthful fault scarps, and several flat-floored grabens, including Sam's Neck and Pleasant Valley, project beyond the main depression between parallel horsts.

Separating Butte from Shasta Valley is the third topographic unit, the High Cascades. Near the southern edge of the quadrangle this includes the foothills of Mount Shasta; then, in a broad, north-south belt, follows a series of giant volcanoes. Some of these, for instance Miller and Eagle Rock Mountains, are considerably eroded, while others, like the Goosenest and Whaleback, are so recent in origin that they have been modified only slightly by dissection. Their summits rise to elevations of approximately 7,000 to 8,500 feet. Those built of basaltic lavas have gentle slopes that contrast strikingly with the steep flanks of the andesitic cones.

In the High Cascades the topography is almost wholly constructional, the land-forms resulting chiefly from the outpouring of lava during Pliocene and later times; to the west, on the other hand, where Eocene, Oligocene, and Miocene volcanic rocks are exposed, the topography is entirely erosional and bears no relation to the shapes of the original cones from which the lavas and ashes were erupted. This topographic contrast is accentuated by a pronounced difference in vegetation, for the young volcanoes of the High Cascades are heavily wooded while the older volcanic rocks, being for the most part thickly mantled with soil, form rounded, grassy slopes and cultivated fields.

The fourth topographic unit is the valley of the Klamath River. Where it is incised into the older volcanic rocks, the landscape is mature and the streams flow in V-shaped channels between branching, narrow-crested ridges; where it crosses the High Cascades, on the other hand, the topography is youthful and the streams occupy deeper, narrower canyons bordered by plateaus and flat-topped spurs. The course of the Klamath River, like that of the Rogue and the Umpqua, was already established in broad outline before the older volcanic rocks were raised and tilted to the east, and before the uplift of the Klamath-Siskiyou Mountains. Prior to Pliocene time, the river already flowed westward through a broad valley crossing the eastward-dipping lavas, and although the bedrock region to the west rose spasmodically the river maintained essentially its present course by incising a deep canyon through the Klamath Mountains. In brief, the Klamath River is an antecedent stream.

Climate and Vegetation

Except that the winter temperatures are lower, the climate of Shasta Valley resembles that of the Sacramento Valley. At Yreka, the mean annual rainfall approximates 18 inches, and at Montague it is about 12 inches, the rainy season lasting from October to April. "The mean annual temperature is 51.3° F. During the rainy season it averages about 40°F. It drops to zero at times, and snow falls nearly every winter . . . . From May to October, inclusive, the average is 62°F. Summer temperatures above 100°F. are often recorded, although these extremely hot periods do not last long . . . . The climate is well suited to stock raising and grain growing, which are the principal industries." [1]

The climate of Butte Valley conforms closely to that of the Great Basin region of Oregon. At Klamath Falls, about 20 miles north of Butte Valley, the rainfall averages approximately 15 inches a year; at Macdoel the annual rainfall is about the same, while the seasonal snowfall averages approximately 44 inches. Most of the precipitation falls during the winter months; between June and September only about half an inch falls per month.

In the High Cascades the rainfall is considerably heavier and winter snows are common. Here the mountains are covered with a heavy growth of yellow pine, Douglas spruce, white fir, incense cedar, and tamarack pine, and scattered groves of aspen, maple, and oak. Where these forests

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[1] Watson, E. B., Wank, M. E., and Smith, Alfred, Soil survey of the Shasta Valley area, California. U. S. Dept. Agriculture, Bur. Soils, 1923.

have been destroyed by fire, as on Eagle Rock and Willow Creek Mountains, they have been replaced by wide areas of brush that are difficult of access.

Butte and Shasta Valleys and the hills bordering the Klamath River are given over mainly to grain and pasture. The swamps of Butte Valley are covered with tule grass which furnishes grazing and wild hay, while the southern part of the valley is thinly covered with yellow pine.

Acknowledgments

Portions of the field seasons of 1935 and 1936 were devoted to a reconnaissance of the area as part of a program of study of the southern Cascades. During 1948, six weeks were spent in completion of the work. Thanks are recorded to the Board of Research of the University of California for funds that helped to defray expenses.

For much information concerning the local geology and for pleasant companionship in the field, I am grateful to Messrs. Walter Pollock, Sr. and Jr., of Yreka, and to Mr. C. B. Kay of Montague.

DESCRIPTIVE GEOLOGY

The oldest rocks in the Macdoel quadrangle are metacherts and quartzites exposed on Yellow Butte, part of a narrow fault block at the foot of Mount Shasta. Similar rocks, accompanied by siliceous schists and marbles and intruded by sills of metadiabase and serpentine are widespread along the edge of the Siskiyou Mountains, immediately to the west of the quadrangle (pl. 4). The age of the metamorphic rocks is problematical, but probably Paleozoic. On Yellow Butte they are intruded by quartz monzonite, presumably of Jurassic age.

No Cretaceous rocks outcrop within the Macdoel area, but the presence of many salt-water wells and springs in and around Shasta Valley suggests that marine Cretaceous beds underlie much of the quadrangle. A short distance to the west, near Yreka and Montague, and to the northwest, in the valley containing Hornbrook and Hilt, Upper Cretaceous (Chico) sediments are widely exposed. Everywhere they rest with profound unconformity on the plutonic and metamorphic bedrocks.

Lying upon the Cretaceous beds are Eocene sediments that belong to the Umpqua formation. In the Coast Ranges of Oregon, around Roseburg and farther north, these beds are marine and include abundant flows of pillow basalt, but to the south, in the Medford, Yreka, and Macdoel quadrangles, they are all of freshwater origin and consist mainly of shales, sandstones, and conglomerates with a few thin beds of coal. They outcrop in two parts of the Macdoel region, one at the northern end of Shasta Valley, and the other close to the eastern edge, at the foot of Miller Mountain.

By far the greater part of the Macdoel quadrangle is occupied by Tertiary and Quaternary volcanic rocks. The western half is made up principally of lavas and pyroclastic beds that range in age from Eocene to Miocene. These belong to the Western Cascade series [2] which forms the coastward flank of the Cascade Range throughout its length. Within this belt the landscape is entirely erosional in origin; no trace remains

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[2] Callaghan, Eugene, Some features of the volcanic sequence in the Cascade Range in Oregon: Am. Geophysical Union Trans., pp. 243-249, 1933.

of the cones and craters from which the flows and ashes were discharged, and only a few plugs are left to mark the sites of the central pipes of some of the vanished volcanoes.

At the close of the Miocene epoch, the Western Cascade series was gently tilted toward the east and northeast and cut by faults trending slightly west of north. Subsequently a broad, north-south chain of large volcanoes was built. Because these form the crowning peaks of the Cascade Range, their products are grouped together as the High Cascade series. During Pliocene and early Pleistocene times the eruptions were mostly of olivine basalt and olivine-bearing basaltic andesite. These produced such huge, flattish shield volcanoes as Miller and Eagle Rock Mountains. At the same time, viscous flows of andesite and dacite (?) were discharged by other volcanoes along the crest of the range. Mount Shasta itself was built mainly during the Pleistocene epoch, at first almost wholly by effusions of andesitic lava, but in the final stages by eruptions of dacite and basalt as well.

After the close of the Pleistocene epoch, while the glaciers of Shasta were retreating to their present position, many new volcanoes were formed and many of the older shield volcanoes, particularly along the borders of Butte Valley, were much modified by block faulting. Among these younger volcanoes, the Whaleback and Deer Mountain were the first to develop; subsequently the Little Deer Mountain and Goosenest volcanoes became active. Long flows of olivine basalt flooded the canyons of Butte and Alder Creeks and others spread over the eastern half of Shasta Valley. Still later, the Klamath River was dammed by eruptions of basalt near Copco Dam. The final eruptions within the area may have taken place within the last millennium; certainly numerous flows issued no more than a few thousand years ago. The last explosions of the neighboring Mount Shasta probably occurred in 1786.[3]

Pre-Cretaceous Bedrocks

The only exposures of the pre-Cretaceous basement within the quadrangle are on Yellow Butte, at the northern base of Mount Shasta, where they form part of a narrow, north-trending fault block bordered by Pleistocene and Recent lavas.

This bedrock island consists mainly of dense, almost porcelanic, pale bluish-white quartzites, in places finely banded in shades of pale gray and black. In part, at least, they are metacherts. The bedding rarely departs more than 10° from the vertical, and the strike, while dominantly north, ranges from north-northeast to north-northwest. Near the southern end of the butte, thin beds of mica schist and slate accompany the quartzites. Along the eastern flank, the metamorphic rocks are cut by coarse-grained hornblende-biotite quartz monzonite and thin dikes of aplite.

By analogy with the bedrocks of the Siskiyou Mountains, the metamorphic rocks are assigned to the Paleozoic, and the plutonic rocks are referred to the Jurassic period.

Attention is directed next to the bedrocks that border the Macdoel quadrange on the west, the distribution of which is shown in plate 4. The

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[3] Williams, Howel, Mount Shasta, a Cascade volcano: Jour. Geology, vol. 40, pp. 417-429, 1932.

Williams, Howel, Mount Shasta, California: Zeitschr. für Vulkanologie, vol. 15, pp. 225-253, 1934.

hills extending southeastward from Yreka to Grenada consist chiefly of siliceous metasediments overlain by Cretaceous sandstones and conglomerates. Predominant among the metamorphic rocks are banded metacherts and dense quartzites, some of which carry a little graphite. Next in order of abundance are pale gray and buff quartz-sericite schists and pale green quartz-chlorite schists, presumably derived from either siliceous tuffs or impure feldspathic sandstones. In quite subordinate amount are lenses of marble and of quartz-epidote-albite-chlorite schists, the latter representing metamorphosed basic tuffs.

A noteworthy feature of the siliceous schists, metacherts, and quartzites in these hills is the abundance of thin veinlets of quartz of irregular trend. All appear to be barren of ore.

The attitudes of these metamorphic rocks vary greatly even over short distances, and in particular the sericitic schists and metacherts show intense crumpling. In general, however, the dips are less than 40°.

Similar metamorphic rocks stretch northward beyond the Yreka-Montague road, along Bedford Ridge and the eastern flank of Paradise Crags. In this direction, stringers and eyes of marble become more plentiful and beds of quartz-epidote-albite-chlorite schist increase both in number and thickness. Concurrently the structure becomes simpler; the beds no longer roll at low angles in all directions but generally strike to the northeast and stand either vertically or dip at high angles.

Many sills of serpentine intrude the metamorphic rocks just described, some of them measuring only a few feet in width, others ranging up to a mile across. Locally these intrusions contain pods of gabbro, and along their contacts the serpentine is often accompanied by a small amount of talc. Adjacent to some intrusions, the quartzites and metacherts are converted to glaucophane schists some of which carry lawsonite and radiating tufts of biotite.

The metasediments and tuffs are also intruded by a body of metadiabase more than 3 miles in width. This forms most of the Paradise Crags, and is cut by U. S. Highway 99 as it follows the gorges of the Shasta and Klamath Rivers. Locally the diabase is somewhat schistose, but for the most part it is a massive, strongly jointed, pale-green rock, thoroughly chloritized and containing much calcite, epidote, and prehnite accompanied by albitized feldspar.

Little is known concerning the age of these rocks. Averill[4] assigns the metamorphics to the early Paleozoic or pre-Paleozoic eras. Wells,[5] in describing the southwest corner of the Medford quadrangle, divides the metamorphic rocks there into an older, highly foliated group of chlorite, epidote, and sericite schists and a younger group of less foliated rocks composed mainly of quartzites, quartz-mica and quartz-amphibole schists, argillites, and marbles. Probably the latter group is equivalent to the rocks just described from the Macdoel and Yreka quadrangles, but Wells simply assigns them to a pre-Mesozoic age.

Whether or not the metadiabase of Paradise Crags is also to be classed as pre-Mesozoic is uncertain, but the serpentine is probably Jurassic, like the quartz monzonite of Yellow Butte.

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[4] Averill, C. V., Preliminary report on economic geology of the Shasta quadrangle: California Div. Mines Rept. 27, pp. 2-65, 1931.

[5] Wells, F. G., Preliminary geologic map of the Medford quadrangle, Oregon: Oregon Dept. Geology and Min. Ind., 1939.

Upper Cretaceous (Chico) Beds

A strong unconformity separates the Jurassic and older bedrocks from the Upper Cretaceous sediments now to be discussed. Although these sediments do not outcrop within the Macdoel quadrangle, they are believed to be present at shallow depths under Shasta Valley and they are widely exposed a short distance to the west, as shown in plate 4.

Typically the Chico formation consists of greenish-gray, arkosic sandstones that weather to buff and deep brown crusts. In general the sandstones are firmly cemented with calcite and limonite. Massive beds, several feet in thickness, alternate with layers from a fraction of an inch to a few inches thick. Beds of conglomerate recur at many horizons, but they are thickest, coarsest, and most plentiful near the base of the formation. Conversely, bluish-black shales, rich in calcareous and ferruginous concretions, become more numerous in the upper part of the formation.

Because the Chico beds were laid down on an uneven surface cut in many types of bedrock, the conglomerates show wide variations. For instance, where the basal conglomerates cross the Klamath River, about a mile below Camp Lowe, they are crowded with pebbles and cobbles of metadiabase. On the Richardson Ranch, near the former site of Snowdon School, the constituent pebbles are composed mostly of milky quartz, quartzite, and black chert, accompanied by porphyries and quartz diorites.

The Chico sandstones likewise vary with the character of the adjacent bedrocks, but to a less extent. Where they were derived from metavolcanic and basic plutonic rocks, they are green arkoses and graywackes rich in ferromagnesian minerals; where the source rocks were quartz-mica schists, quartzites, and metacherts, they are pale, micaceous, quartz-rich sediments; where their provenance was among the acid and intermediate plutonic rocks of the Klamath-Siskiyou Mountains, they are light-colored arkoses liberally sprinkled with hornblende and biotite.

In the valley of Cottonwood Creek, near Hornbrook and Hilt, and along the flanks of Black Mountain, the prevailing dips are toward the northeast at angles of 15° to 25°; exceptionally, the dip increases to 30°. Near Yreka and Montague, on the other hand, eastward and northeastward dips diminish to between 10° and 20°.

Thickness and Buried Extent. In the Medford quadrangle, the Chico formation reaches a maximum thickness of 400 feet.[6] In the northeast corner of the Yreka quadrangle, no accurate measurement is possible owing to the difficulty of distinguishing between the upper, shaly phase of the Chico and the overlying Umpqua formation. The minimum thickness of the Chico beds west of Hornbrook is about 1,000 feet; on the northeast flank of Black Mountain, the beds are probably between 1,100 and 1,500 feet thick; among the outliers close to Montague, only the lower part of the formation is present to thicknesses of a few hundred feet.

Between the Oregon-California boundary and the northern end of Shasta Valley, the formation is overlain disconformably by Eocene (Umpqua) sediments which are covered in turn by Eocene volcanic rocks. Southward the volcanic rocks gradually overlap the Umpqua and Chico beds until, between Montague and Grenada, they rest directly on

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[6] Wells, F. G., op. cit.

the metamorphic bedrocks. There is reason to suppose, however, that both the Chico and Umpqua formations continue eastward at depth, at least under Shasta Valley and perhaps under the Cascade Range as well. Only a thin cover of alluvium conceals the Chico beds in the flat area between the Southern Pacific Railroad and the base of Paradise Crags. An artesian well sunk near Shasta River, about 2 miles south of Montague, after passing through volcanic rocks to a depth of 148 feet, entered sandstones with marine fossils at depths of 285 and 317 feet.[7] The copious flow of salt water that issued was formerly evaporated to manufacture salt, and it is said that for several years in the late eighties gas escaping from the water was piped and burned.[8] The presumption is that this gas came from carbonaceous material either in the Chico or, more likely in the Umpqua formation, and almost certainly the salt came from marine Cretaceous sandstones. The presence of other saline springs, such as the Beswick Hot Springs on the Klamath River, the Soda Springs near Bogus School, and the carbonated springs near Table Rock, suggests that Chico beds continue underground far to the east.

Age and Correlation. According to F. M. Anderson,[9] two distinctive fossil horizons are to be seen in the Chico formation. The lower one, below the middle of the sandstones, near U. S. Highway 99, both in Rocky Gulch and west of Hornbrook, contains numerous species of marine bivalves and gastropods, including *Trigonia evansana* Meek, *Chione varians* Gabb, *Glycymeris veatchi* Gabb, *Cucullaea decurtata* Gabb, *Gyrodes expansa* Gabb, and *Amauropsis oviformis* Gabb. "At the junction of the uppermost sandstone beds and the overlying shales is the second notable zone of fossils, which contains few of those found in the lower zone, but instead a considerable variety of cephalopod forms" such as *Pachydiscus henleyensis* Anderson, *Barroisiceras knighteni* Anderson, *Placenticeras pacificum* Smith, *Placenticeras californicum* Anderson, and *Barroisiceras siskiyouensis* Anderson. On the Richardson Ranch, between Ager and Montague, the following species are recorded by Anderson from a lower horizon of the same zone:

Desmoceras klamathae n. sp.
Desmoceras yoloense n. sp.
Mortoniceras crenulatum Anderson
Phylloceras ramosum (Meek)
Pachydiscus siskiyouensis n. sp.
Puzosia hearni n. sp.

At this locality, one of the layers of sandstone is unusually rich in sharks' teeth; others are typified by many gastropods, while still others are rich in *Trigonia* and ammonites.

Anderson concluded that the cephalopod horizons correspond to the upper Turonian and lower Senonian divisions of the European time scale, and that the zone rich in bivalves and gastropods represents a position about the middle of the Turonian division. He suggested further that the upper part of the Hornbrook section, consisting mainly of shale, as well as the coal-bearing beds south of Ager, might also be of Cretaceous age. It seems more probable, however, that these belong to the Umpqua (Eocene) formation to be described in the sequel.

Mode of Deposition. During much of late Cretaceous time, the present site of the southern Cascades and the flanks of the Klamath-

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[7] Wells, H. L., History of Siskiyou County, Oakland, 1881.
[8] Huseman, K. P., The King Salt Works: Siskiyou County Hist. Soc., vol. 1, pp. 17-22, 1947.
[9] In Averill, C. V., op. cit., pp. 10-14.

Siskiyou Mountains were largely if not entirely occupied by a shallow sea. The predominance of sandstones among the Chico beds, the prevalence of conglomerates and breccias, the presence on many horizons of much carbonaceous material and of large, shallow-water fossils, as well as the rapid variation in the composition of the Chico formation according to the nature of the adjacent bedrocks, all indicate near-shore, marine deposition and imply a neighboring landmass of moderate to rugged relief undergoing fairly rapid erosion under a climate that favored mechanical rather than chemical weathering.

Eocene (Umpqua) Sediments

Sediments of Eocene age outcrop in two widely separated parts of the Macdoel quadrangle, one near Ager and the other close to the eastern edge of Shasta Valley, at the foot of Miller Mountain. Presumably similar sediments underlie the whole of Shasta Valley.

On the adjacent Yreka quadrangle (pl. 4), these Eocene beds can be followed in a narrow belt stretching from the flanks of Black Mountain northward across the Klamath River and along the valley of Cottonwood Creek through Hornbrook and Hilt to the Oregon-California line. Farther north, in the Medford quadrangle, they occupy most of the floor of Bear Valley.[10] Throughout this stretch of approximately 60 miles the Umpqua formation appears to be wholly of freshwater origin. Still farther north, however, in the vicinity of Roseburg, the formation is marine and includes numerous flows of pillow basalt.

Within the Medford quadrangle, and probably within the Yreka and Macdoel quadrangles also, the formation rests disconformably upon the Chico beds. In the northern part of the Medford quadrangle, it grades upward into fluviatile volcanic sediments of Eocene age, but in the southern part an angular discordance separates the Umpqua from the overlying volcanic rocks. Discordance also characterizes the upper contact farther south, so that the exposed thickness of the Umpqua beds rapidly diminishes until, in the neighborhood of Grenada, the volcanic rocks overlap onto the pre-Cretaceous basement.

F. G. Wells [11] estimates that in the Medford region the Umpqua reaches a maximum thickness of not less than 8,000 feet. In Cottonwood Valley, between Henley and Hornbrook, the thickness is reduced to approximately 1,600 feet. On the shoulders of Black Mountain, the thickness ranges from 800 to 1,200 feet. In the disconnected outcrops east of Shasta Valley, the paucity of exposures precludes an accurate estimate, but probably the exposed thickness there is between 1,500 and 2,000 feet.

The Umpqua beds show lateral variations hardly less pronounced than those of the Chico formation. In the southernmost outcrops, at the foot of Miller Mountain, they consist of buff and white, massive sandstones with pebbly layers rich in round fragments of milky quartz and black chert. At the northern end of Shasta Valley, near the Richardson Ranch and Snowdon School, massive beds, 3 to 6 feet thick, alternate with flaggy sandstones less than an inch in thickness that exhibit well-marked cross-bedding. Grains of quartz and feldspar are present in about equal amount, together with a little mica. On account of the paucity of ferro-magnesian minerals, and in particular of chlorite and hornblende,

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[10] Wells, F. G., op. cit.

[11] Op. cit.

none of the sandstones have the greenish colors or the deep brownish crusts typical of the Chico sandstones. Moreover they are rarely as well cemented, being for the most part rather friable and loosely held together by a small amount of calcite and kaolin. Locally, they are seamed with limonite, and one sandstone bed grades into a lens up to 6 feet thick and a few hundred feet long almost entirely composed of limonite and magnetite. The microscope reveals this highly ferruginous layer to be composed of the following constituents: detrital grains of quartz, epidote, augite, and garnet, with minute fragments of quartzite and plutonic rocks, 10 percent; ovoid and subangular grains of magnetite, mostly 0.1 of a millimeter across, 55 percent; limonitic matrix, 35 percent. It may be considered as an impure bog iron ore.

Close to the Ager-Montague road, about 5 miles south of Ager, and approximately 300 feet stratigraphically above the top of the Chico formation, the sediments just described are overlain by a bed of coal having a maximum thickness of 6 feet (see p. 57). Above this, the Umpqua formation consists mainly of bluish-gray shales and silty shales with many thin intercalations of ferruginous sandstone. On the steep slopes of Black Mountain these beds are poorly exposed owing to long slides of debris from the overlying lavas. Above Camp Lowe, on the northwest flank of the mountain, the shales are interrupted only by a single, though persistent bed of flaggy sandstone, 6 feet thick.

North of the Klamath River, in the valley of Cottonwood Creek, the lateral variations are even more pronounced. Banded shales and silty shales still predominate, but layers of tuffaceous material increase in number and thickness toward the Oregon-California boundary, particularly in the upper part of the formation, and near Hilt a few flows of lava appear just beneath the top. In this direction, beds of coarse, quartz- and mica-rich sandstone, crowded with shale pebbles and carbonaceous specks and with occasional carbonized logs, become increasingly common. Many of these sandstones show strong cross-bedding and alternate with layers of conglomerate from a few inches to 15 feet in thickness, carrying large boulders of siliceous bedrocks. Still farther north, in the Medford quadrangle, the Umpqua beds are composed mainly of white to light-brown, medium-grained sandstones admixed with tuffaceous material.[12] Shales and conglomerates containing abundant pebbles of quartzite recur at many horizons, and near Ashland and Talent there are intercalations of coal.[13] Lavas increase in number near the top.

Age and Mode of Deposition. According to Knowlton,[14] fossil floras in the coals near Ashland indicate an Eocene age. Unfortunately no detailed study has been made of the leaves associated with the coal near Ager, but there is no reason to doubt that this coal is also of Eocene age. No other fossils have been found in the formation.

Analysis of the Eocene floras of Oregon by Chaney [15] indicates that the climate of Umpqua time was subtropical. Under these conditions, chemical weathering of the bedrocks in the Klamath-Siskiyou Mountains, which were then much lower than at present, was more pronounced than

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[12] Wells, F. G., op. cit.

[13] Diller, J. S., The Rogue River Valley coal field, Oregon: U. S. Geol. Survey Bull. 341, pp. 401-405, 1907.

[14] In Diller, op. cit., p. 405.

[15] Chaney, R. W., Ancient forests of Oregon: Cooperation in Research; Carnegie Inst. Washington Pub. 501, 1938.

during the Cretaceous; hence the Umpqua sediments tend to be more siliceous and less feldspathic than those of the Chico formation. The prevalence of cross-bedding and channeling in the Umpqua sandstones, and the presence of coarse siliceous conglomerates suggest fluviatile deposition; the shales and silty shales composing the major part of the formation presumably represent deposits laid down on wide alluvial flats bordering sluggish streams that drained a country of low relief to the west. The coals with their clay-ironstone concretions denote the existence of peaty swamps, and possibly the limonitic ore near Ager was laid down in bogs fed by iron-rich waters draining lateritic soils covering the bedrocks. In these respects, the lithology of the Umpqua formation recalls that of the Ione beds of Eocene age, farther south in California.

Western Cascade Series

The Pliocene and younger volcanic cones along the crest of the Cascade Range in California, Oregon, and Washington, are flanked on the west by a belt of older Tertiary lavas and pyroclastic rocks named by Callaghan [16] the Western Cascade series. Throughout this belt the topography is erosional, with no trace of constructional slopes such as typify the High Cascades. Indeed the cones that contributed to the accumulation of the Western Cascade series had not only been erased by erosion but the lavas and ashes erupted from them had already been folded and deeply dissected before the volcanoes of the High Cascades began to develop.

The width of the belt occupied by the Western Cascade series in Oregon ranges generally from 30 to 40 miles. Southward the belt becomes narrower. Along the Oregon-California line, the width is reduced to about 24 miles; in the latitude of Sheep Rock, in the southern part of the Macdoel quadrangle, it is 18 miles; finally, 3 miles south of Weed, the belt comes to an end owing to overlap by lavas discharged from Mount Shasta.

Throughout this long stretch the Western Cascade lavas and fragmental ejecta show prevailing dips to the east and northeast, the angles diminishing in these directions from approximately 15° to almost zero where the series disappears beneath the cones of the High Cascades. East of the High Cascades, coeval volcanic rocks are widespread. Thus in Oregon the Western Cascade series corresponds with the Clarno, John Day, Columbia River basalt, Mascall, and Payette formations of the central plateau; in northeastern California, part of the series is equivalent to the Cedarville beds of the Warner Range.

Because of overlap by the flows of the High Cascade volcanoes, the Western Cascade series is nowhere exposed to its full thickness. Along the Oregon-California boundary the visible beds have a thickness of not less than 12,000 feet, and perhaps as much as 15,000 feet. In the latitude of Yreka, the exposed thickness is reduced to about 10,000 feet. Farther south, several factors, among them the paucity of measureable attitudes, make it impossible to estimate how rapidly the exposed thickness diminishes to zero.

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[16] Op. cit., pp. 243-249.

The Bedded Rocks

Most of the volcanic rocks of the Western Cascade series are pyroxene andesites, though they range in composition from olivine basalt to rhyolite. They differ from the products of the High Cascade cones in the higher proportion of pyroclastic debris and the greater degree of alteration of many of the lavas.

Lavas

Within the Macdoel quadrangle, the dominant flows by far are hypersthene-augite andesites; indeed in the southwestern part these are almost the only lavas. Two principal types are easy to distinguish, one a pale-gray, pilotaxitic variety rich in large phenocrysts of basic plagioclase and pyroxene, and the other a much finer-grained, dark-gray to black variety with fewer phenocrysts and a glassy matrix. They resemble closely the lavas composing the bulk of Mount Shasta. Hypersthene usually predominates over augite. Some flows carry sparse crystals of olivine, mainly replaced either by antigorite and iddingsite or by a mixture of magnetite and hematite, and occasional flows contain a little biotite. In most, the groundmass, whether glassy or cryptocrystalline, includes a small amount of cristobalite or tridymite.

Few andesites are notably vesicular, and scoriaceous tops and bottoms of flows are exceptional. Fluidal banding is seldom distinct. Some of the more glassy flows exhibit crude columnar jointing, but typically the lavas are marked either by widely spaced, blocky joints or by closely set, platy joints that curve upward from the horizontal to the vertical. The latter are to be ascribed to shearing of the flows during the final stages of advance. Most of the lavas measure between 10 and 30 feet in thickness, but a few, such as that forming the mesa between Brush and Dry Creeks, exceed 100 feet in thickness.

Among the Western Cascade andesites in Oregon, hydrothermal alteration is widespread, especially in the vicinity of dioritic stocks and along mineralized belts. In such places the rocks may be thoroughly decomposed, the feldspars being altered to sericite, kaolin, calcite, and epidote, while the original ferromagnesian constituents are changed to uralite and chlorite. Perhaps because of the absence of dioritic stocks and mineralized belts, the Western Cascade andesites in the Macdoel quadrangle show much less alteration. In the upper part of the series, however, many of the lavas have been converted to greenish propylites, in which the feldspars are kaolinized and the pyroxenes are replaced by calcite, chlorite, and limonite.

In many andesites, particularly in those approximately halfway to two-thirds way up in the series, veins and amygdules of opal and chalcedony are plentiful. For instance, on Agate Flat, carnelian, jasper, and white and gray banded opals and agates have weathered out in profusion from the lavas and much petrified wood is to be found among the interbedded tuffs.

Hornblende-bearing pyroxene andesites and hornblende andesites are much less common than those devoid of amphibole. A few are present east of Shasta Valley, near Table Rock and Davis Gulch, and others outcrop on the south slopes of Bogus Mountain, but it is chiefly in the volcanic necks rather than in the flows that hornblendic varieties of andesite are to be found.

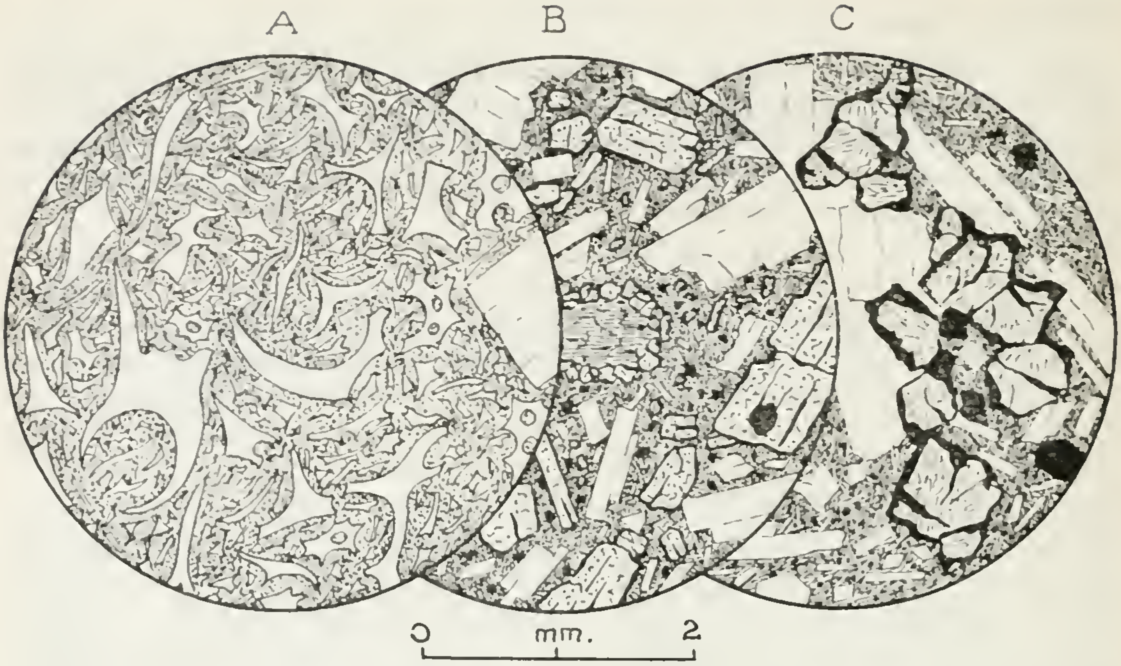

FIG. 2. Microdrawings showing Western Cascade rocks. *A*, Rhyolitic vitric tuff (122), from near Bogus Soda Springs. Curved shards of glass in a matrix of glass dust, the whole now devitrified. Also part of a plagioclase phenocryst. *B*, Vitrophyric pyroxene andesite (89), from 2 miles south of Ager. In center, a phenocryst of olivine altered to talc and antigorite and surrounded by a rim of augite. Other phenocrysts consist of plagioclase, hypersthene, and augite. The matrix consists chiefly of brown glass stippled with granules of ore and microliths of feldspar. *C*, Olivine basalt (121), from half a mile southwest of Bogus Soda Springs. Phenocrysts of olivine, mainly replaced by talc and bowlingite and rimmed with magnetite; also phenocrysts of calcic labradorite, microliths and minute granules of pyroxene, chiefly augite, and opaque ore minerals.

Flows of dacite are also rare. A few occur near the base of the series, in the hills south of Ager. These show considerable hydrothermal alteration. Originally, hornblende was the main ferromagnesian constituent, and in some dacites it made up about a quarter of the volume. All of it is now replaced either by granular magnetite or by a mixture of calcite and chlorite. The forms of some calcite-chlorite aggregates suggest that phenocrysts of pyroxene were also present in small amount. Zoned phenocrysts of acid labradorite-medium andesine make up approximately a third of a typical dacite, while porphyritic quartz ranges in amount from 1 to 5 percent. All these constituents lie in a micro- to crypto-felsitic base stippled with opaque ore minerals,[17] secondary quartz, and calcite. In brief, these are silicified and propylitized hornblende dacites.

Higher in the series, dacites are exceptional. One long flow parallels the road, approximately 2 miles south of the summit of Bogus Mountain. In this, phenocrysts of green hornblende, up to 3 millimeters long, make up between 10 and 15 percent of the bulk. Flakes of brown biotite (2 percent), and phenocrysts of zoned acid labradorite-basic andesine (20 percent), accompany the hornblende in a microfelsitic base rich in quartz.

No flows of rhyolite were observed, although rhyolite tuff is abundant and rhyolitic lava forms many domes.

Numerous chemical analyses would be required to determine the proportion of basaltic lavas in the Western Cascade series, for in the field it is seldom possible to distinguish between them and the dark

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[17] In this description and in other petrographic descriptions in this paper, the author has used the term "ore" with reference to the dark opaque minor accessory minerals appearing under the microscope.

andesites, and even under the microscope the distinction is not easy to draw. Available evidence suggests that basaltic flows are most common near the base of the series in the northern part of the quadrangle, especially close to Willow Creek and the Klamath River. An excellent example of a columnar flow of olivine basalt on the banks of the Klamath has been illustrated elsewhere by Averill.[18] Several flows of coarse, ophitic, olivine-augite basalt and of black, dense, intergranular augite basalt are present higher in the series, for example, near the top of Bogus Mountain; but compared with the Pliocene and younger lavas of the High Cascades, the Western Cascade series is strikingly poor in both olivine basalt and olivine-bearing basaltic andesite.

From the foregoing it will be seen that while the Western Cascade lavas show a wide range in composition, they exhibit no regular sequence suggestive of progressive differentiation.

Pyroclastic Rocks

Andesitic and Basaltic Ejecta. By far the largest accumulation of these ejecta is to be seen on Sheep Rock. Here beds of coarse andesitic tuff-breccia, composed of angular and subangular blocks up to 4 feet across in a tuffaceous matrix, reach a total thickness of 1,600 feet. Within this vast pile not a single flow was detected. Many individual layers of breccia, some of which are more than 100 feet thick, show no stratification, although a crude bedding is produced by alternation of layers of slightly different coarseness. Generally the layers dip eastward at about 20°, but locally they roll at low angles in various directions and exhibit large-scale cross-bedding. These variations are not to be ascribed to folding, but are original features of the deposits. Presumably the beds represent chaotic deposits of bouldery volcanic mudflows (lahars) rather than the products of glowing avalanches, for they lack the microvesicular and pumiceous matrix common to the latter and they show no signs of secondary, fumarolic activity. Nor do the Sheep Rock tuff-breccias contain rounded bombs and lapilli indicative of discharge in a partly molten condition. Similar deposits are found elsewhere in the quadrangle, as for instance on the 3468 (Terwiliger) ridge, northwest of Little Shasta, on the south slopes of Bogus Mountain, and along the Klamath River below its confluence with Brush Creek. Some of these deposits contain waterworn boulders and grade laterally into volcanic conglomerates, thus lending support to the view that they were laid down by torrential lahars.

A different kind of mudflow deposit is revealed in a large quarry about 2 miles south of Snowdon Station, not far above the base of the series. In this, angular and subangular blocks of andesite and quartzite, together with a few of rhyolite, measuring up to 4 feet in diameter, lie chaotically in a thoroughly decomposed matrix of unbedded tuffaceous red and brown clay.

Well-stratified, coarse andesitic tuff-breccias and lapilli-tuffs occur between flows of andesite a short distance southeast of the Hessig Ranch, near the Klamath River. Most of the larger fragments measure a few inches across, but some reach a yard in greatest dimension; all are angular and lie in a groundmass of tuff. The outcrop of these beds is

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[18] Op. cit., p. 25, 1931.

almost semicircular, as shown on the geologic map (plate 1), and their quaquaversal dips range up to 50°. To some extent this curvature results from deformation, since it is shared by the associated lavas, but in the main it is a primary feature and indicates the former existence of a steep-sided fragmental cone at this locality.

True agglomerates, that is coarse pyroclastic rocks chiefly composed of rounded lapilli and bombs blown out in a plastic condition, are confined to a few thin beds of basaltic composition close to Willow Creek, below Ager, and along the Klamath River near the western edge of the quadrangle.

As for andesitic and basaltic tuffs, it is impossible to say how common they are in comparison with the lavas because they weather readily to a deep-brown or reddish-brown clayey soil, and are only well exposed in artificial cuts and in the walls of canyons. For that reason no effort was made to map individual layers. None were seen in the hillock country forming the western side of Shasta Valley, south of Little Shasta River, but probably much of the cultivated land bordering Shasta Valley on the north and east is underlain by these finer pyroclastic rocks, and it is there that petrified wood is most abundant. In general, the proportion of tuff increases toward the top of the series, where greenish beds crowded with lapilli are extremely common. North of the Klamath River, in the Medford and Yreka quadrangles, the proportion of tuff in the series is much greater, especially toward the base.

Rhyolite Tuffs. The principal beds of rhyolite tuff are shown on the geologic map, plate 1. They are to be found chiefly in the upper part of the series in the northern part of the quadrangle. Because their colors range from almost white to cream and pale bluish green, they are recognizable in the field even at a distance. Some consist almost wholly of devitrified glass dust; many are crystal-vitric tuffs in which phenocrysts of quartz, orthoclase, andesine, biotite, and hornblende are set in a matrix showing perfect vitroclastic texture; others are coarse, loosely coherent pumice-tuffs and lapilli-tuffs marked by distinct stratification; and still others are firmly welded, streaky tuffs that closely resemble lavas. Examples of the dense, dust-tuffs may be seen near the top of Bogus Mountain and around the headwaters of Little Bogus Creek. At the latter locality they reach a thickness of 500 feet. They carry only sporadic crystals of quartz, feldspar, and biotite in a devitrified and silicified groundmass riddled with veinlets of quartz. Despite their great thickness they show almost no trace of bedding.

The most extensive sheet of rhyolite tuff is traceable for more than 5 miles, passing close to Bogus School. Both laterally and vertically it exhibits marked variation. Locally it is an incoherent rock rich in white fragments of pumice up to an inch in length; elsewhere it is a compact crystal-vitric tuff almost devoid of pumice lumps but containing abundant phenocrysts; in other places, particularly toward the base of the layer, it is a streaky, welded tuff or ignimbrite. Lithic chips of andesite are scattered sporadically throughout. A quarter of a mile north of where the tuff crosses the Ager-Beswick road, close to the bottom of the bed, there is a vertical dike of glassy rhyolite, approximately 10 feet wide, that strikes N. 75° E. Except for the lack of pumice fragments, the dike rock resembles the dense variety of crystal-vitric tuff, and for that reason it is considered to be the filling of one of the fissures from which the tuff was erupted. Cavernous-weathering, welded pumice-tuff forms a line of cliffs on the north side of the Klamath River a short distance below Beswick; other less welded tuffs are exposed near Dewey Gulch and Dry Creek, one of which extends southward through the depression between Table Rock and Solomon's Temple. Probably these were also discharged from fissures after the manner of glowing avalanches, like the tuff erupted on to the floor of the Valley of Ten Thousand Smokes, Alaska, in 1912.

In strong contrast to the tuffs just described are the well-bedded white lapilli-tuffs near the head of Shovel Creek. These carry abundant lumps of rhyolitic pumice and angular fragments of andesite in a matrix of crystal-vitric tuff. Their maximum thickness approximates 500 feet. These ejecta cannot have been laid down by glowing avalanches for they exhibit gravity sorting within individual layers, while successive layers vary greatly in coarseness and there is an almost complete lack of fine dust. Besides, the tuffs show a large-scale cross-bedding suggestive of the influence of shifting winds on falling ejecta. These features, taken together, suggest that the Shovel Creek tuffs were not discharged from fissures but by eruptions of vulcanian type from volcanic cones.

Dacite Tuffs. Near the eastern foot of Miller Mountain, close to Grass Lake, there are three detached masses of glassy, pumiceous, hornblende-biotite dacite tuff some of which might well be mistaken for lava but for the lateral transition into unmistakable pyroclastic debris. At the western end of the principal mass, the cliff-forming tuff gives place to chalk-white, vitric tuff that resembles papery diatomite. The precise relations between these deposits are obscure.

Under the microscope, the cliff-forming welded tuff is seen to be composed of the following constituents: flattened fragments of glassy pumice poor in crystals, mostly between 1 and 4 millimeters long, 25 percent; colorless to gray pumice and glass shards, 25 percent; broken phenocrysts of acid andesine, 40 percent; green hornblende and brown biotite, 4 percent; granular opaque ore minerals, 4 percent; and lithic chips of andesite, 2 percent. Unlike the rhyolite tuffs of the Western Cascade series, this dacite tuff is not devitrified.

Sediments

In the Medford quadrangle the Western Cascade lavas are separated from the underlying Umpqua formation by volcanic conglomerates and sandstones that reach an aggregate thickness of 2,000 feet.[19] In the northern part of the quadrangle these sediments grade downward into the Umpqua beds, but to the south, close to the Oregon-California boundary, an angular discordance separates them. Still farther south, in the Yreka quadrangle, only a few thin beds of volcanic sandstone and conglomerate underlie the basal flows of the Western Cascade series, and even these disappear south of the Klamath River. On the flanks of Black Mountain, the oldest lavas lie directly on the Umpqua shales; ultimately, as noted already, the basal flows come to rest on the pre-Cretaceous bedrocks from near Grenada to the vicinity of Weed.

Within the Western Cascade series there is also much less interbedded sediment toward the south. A few lenses of tuffaceous sandstone

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[19] Wells, F. G., op. cit.

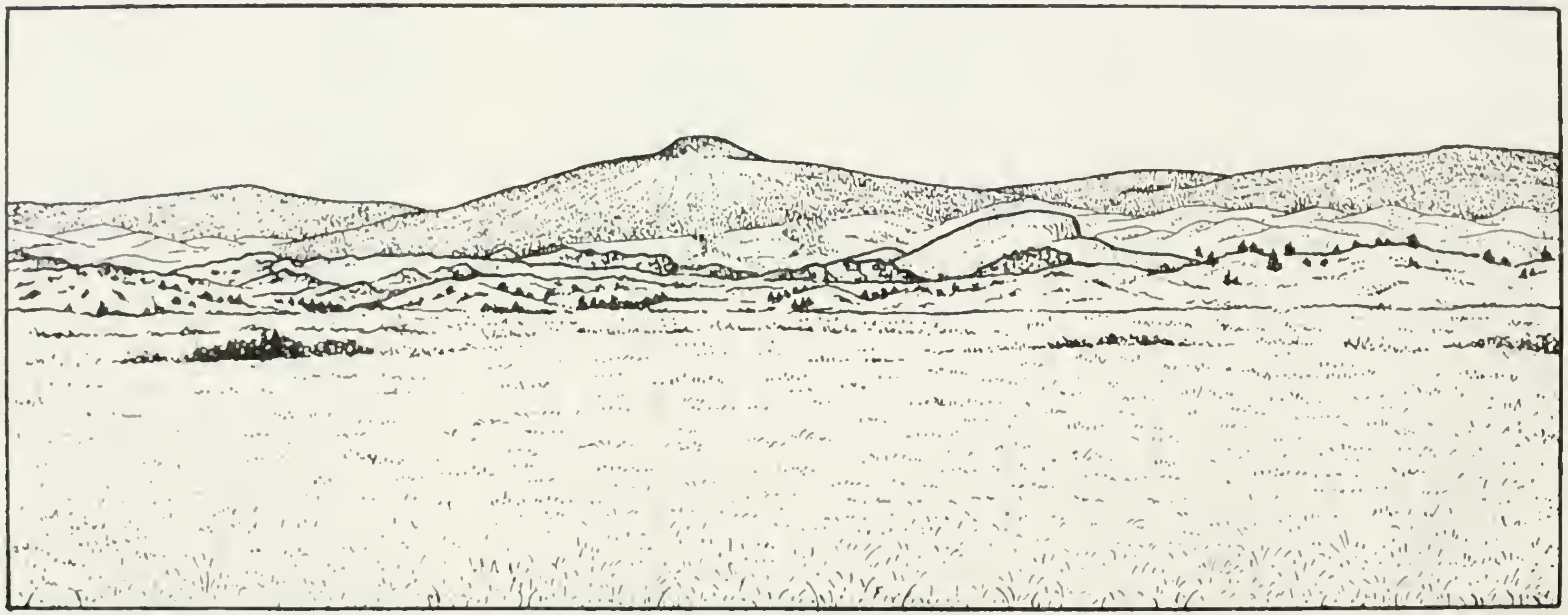

FIG. 3. Looking east across Shasta Valley to the High Cascades. The large, wooded volcanoes in the background are, from left to right, as follows: the andesitic cone of Willow Creek Mountain; the Recent cone of the Goosenest; two basaltic shield volcanoes, the larger forming Miller Mountain. The conspicuous hill in the middle distance, with cliffs on one side, is the rhyolite dome of Drop-off; the other hills consist mainly of andesitic lavas of the Western Cascade series. The contact between the High and Western Cascade series coincides approximately with the line between the wooded mountains and the grass-covered hills. Note the two tongues of Recent lava from the Goosenest; these occupy canyons cut in the older volcanic rocks, near the center of the sketch.

and conglomerate are present close to the base of the series near Klamathon and Hornbrook and in the valley of Willow Creek, and occasional rounded pebbles and boulders in the tuffs thereabouts testify to stream action during deposition. Small lenses of volcanic conglomerate also occur locally in the upper part of the series, as along Davis Gulch. Layers of diatomite, such as are found in the series in Oregon, are lacking, but a seam of coal and carbonaceous shale is interbedded among the volcanic rocks on Glenn Williams' Ranch, between Wallbridge and Davis Gulches.

Volcanic Necks, Domes, and Dikes

Rhyolite Domes

A line of rhyolite domes, trending northeastward, passes close to Cedar Lake, Little Shasta, and Table Rock. The largest one forms a cluster of coalescing hills, some gently rounded and others cliffed and craggy, that culminate in a central peak known locally as Drop-off (3433 Hill on the geologic map, plate 1), rising more than 700 feet above the surrounding flats. These hills consist of white to pale cream rhyolite, so fine-grained that only a few minute crystals of feldspar and biotite are recognizable even with the aid of a hand lens. Where the rhyolite is silicified it is difficult to distinguish from quartzite, and indeed on the map prepared by the geologists of the Southern Pacific Railroad the lava is shown as Paleozoic metamorphic rock.[20] Elsewhere the rhyolite resembles diatomite, and some of it is almost porcelaneous in appearance. Over large areas the only discernible structure is a strong, steeply inclined set of joints of irregular trend, but in places a hair-fine, fluidal banding is developed. On the southwest hill of the cluster this banding generally dips at angles of less than 40°, but on the other hills most of the dips exceed 60°. The strike of the banding is extremely variable over short distances, and many flow planes are minutely contorted, suggesting drag induced by differential upward flow of highly viscous material. Unfortunately, long banks of talus obscure all contacts with the enclosing rocks. There is little doubt, however, that one is confronted here with a group of plug-domes of the Lassen Peak type, in other words with a cluster of viscous protrusions.

About a mile to the northeast of the cluster just decribed two conical peaks, one 280 and the other 400 feet high, rise from the floor of Little Shasta Valley. These are composed of dense, quartzite-like rhyolite almost completely devoid of fluidal banding. Where flow planes can be seen they strike parallel to the length of the hills and dip at angles of more than 70°.

Two small patches of similar rhyolite lie on the flanks of 3266 Hill, close to Little Shasta, one of which has been quarried for road metal, and three other patches, approximately in line, cut opaliferous flows of andesite near Table Rock.

Finally, two isolated masses of rhyolite outcrop near the base of Miller Mountain. The western one consists mostly of lava marked by steeply dipping flow planes but includes some tuffaceous material as well; the other is made up entirely of lava, much of which looks like papery diatomite while some is strongly silicified and massive. These, like the masses of rhyolite in Shasta Valley, are best regarded as domical protrusions.

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[20] Averill, C. V., op. cit.

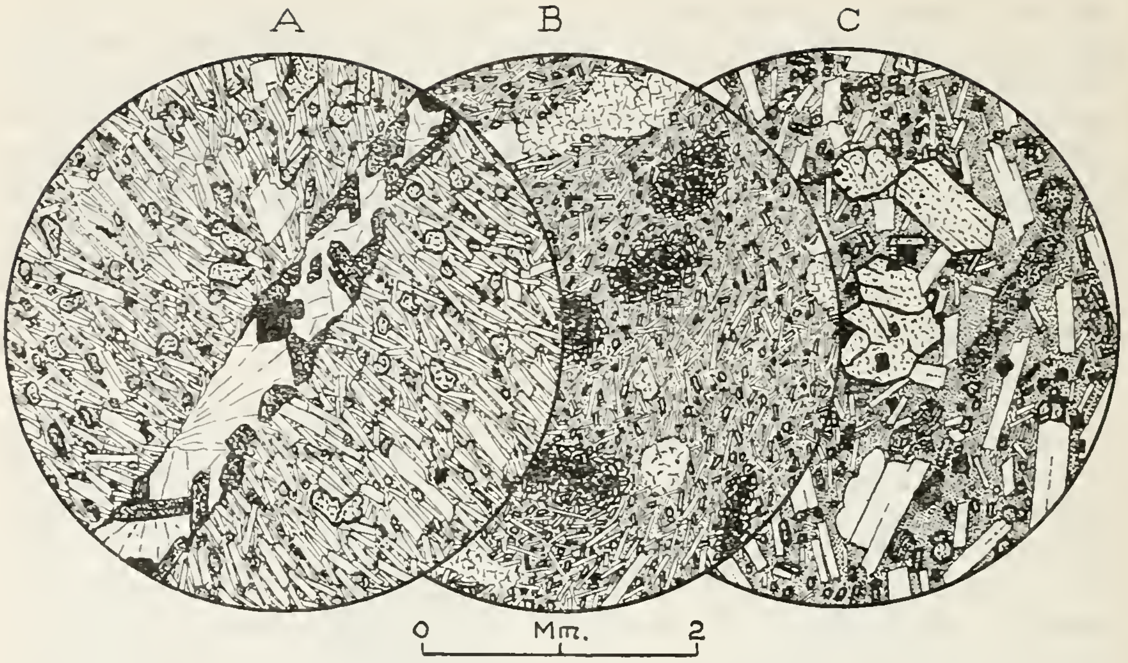

FIG. 4. Microdrawings showing rocks from volcanic necks. *A*, Pyroxene andesite (574) from dike-like neck adjoining the Klamath River below Copco Dam. Bulk of rock is a-fluidally banded aggregate of labradorite laths with intergranular augite, hypersthene, and magnetite, together with a little interstitial cristobalite. Cutting this is a vein composed of stilbite, aegerite, and magnetite. *B*, Cristobalite-rich, hornblende-bearing pyroxene andesite (167) from the western neck near Agate Flat. Phenocrysts of oxyhornblende, almost wholly replaced by augite and opaque ore minerals, in a groundmass of slender labradorite laths, prisms of hypersthene, subordinate augite, and opaque ore minerals. Cristobalite filling irregular cavities throughout. *C*, Augite basalt (165) from the neck adjacent to the Fish Hatchery, near the Klamath River. Phenocrysts of augite and calcic labradorite, together with microliths of the same, in a matrix of dark-brown glass partly altered to deep golden chlorophaeite.

The microscope reveals all the rhyolites to consist essentially of micro- to crypto-felsite, that is of a dense, granular to graphic intergrowth of quartz and orthoclase stippled with magnetite. In some specimens the felsitic base is relieved by acicular microliths of orthoclase and a little acid plagioclase. Phenocrysts of quartz and feldspar are completely lacking. Minute, sporadic flakes of brown biotite are present in the rhyolites of Drop-off and the twin domes to the northeast, but the rhyolites near Little Shasta and Table Rock are devoid of all ferromagnesian minerals. Tridymite forms as much as 5 percent of the rhyolite in the twin dome just referred to, and is sparingly present in some of the other domes. Accordingly the rocks are classed as aphyric potash rhyolites. Their resemblance in mineral composition to some of the rhyolite tuffs suggests that in some cases the rise of the rhyolitic domes was accompanied by explosive eruptions from the same vents.

Necks of Andesite, Dacite, and Basalt

Six necks stand out as conspicuous hills close to the Klamath River, below Copco Dam. These served as feeders to surface flows. Five are of andesite, and one is of basalt.

The two necks overlooking Agate Flat are oval in plan, measuring approximately 2,000 by 1,000 feet, and are elongated in a north-south direction, i.e. parallel to the Cascade Range. The western neck consists of massive, fine-grained, pyroxene andesite, devoid of banding. For the most part the only observable structure is a series of widely spaced, vertical joints of irregular trend, but in places there are multiple dikes that run parallel to the length and exhibit horizontal columns. The adjacent neck also consists of pale gray andesite, but there the irregular, blocky joints of the interior portion give place marginally to closely set, platy joints parallel to a hair-fine, steeply inclined, fluidal banding that is either highly contorted or strikes parallel to the margins. The microscope shows the lava of both necks to be made up of the following constituents: magnetite-augite pseudomorphs after oxyhornblende phenocrysts, 5 percent; euhedral prisms of hypersthene, rarely more than 0.5 of a millimeter long, 15 percent; equally small granules of augite, 5 percent; granular opaque ore minerals, 5 percent; sub-parallel microliths of medium labradorite, 60 percent; pale buff, interstitial glass ($n = 1.520 \pm .002$), 5 percent; and cristobalite, lining pores and cracks, 5 percent.

A third, slightly smaller neck of hornblende-bearing pyroxene andesite towers above the Copco road, a mile northwest of the dam. This one is also elongated in a north-south direction. What chiefly distinguishes it from the others is the abundance of columnar, vertical dikes, up to 10 feet in width, that run parallel to the major axis, and the presence of marginal, tangential or ring dikes that dip outward at angles of 60°-80°. The core of the neck is composed mainly of blocky, aphyric andesite. The peripheral rocks carry numerous slender phenocrysts of hornblende and, on account of the close spacing of their steeply dipping joints, they seem from a distance to resemble fissile slates. Presumably, as in other necks, this marginal platy character was produced by shearing as viscous lava rose differentially toward the surface.

Not far to the south of this third neck there is an imposing wall-like body of andesite, approximately a mile long and trending slightly west of north, around one end of which the Klamath River makes a hairpin bend. Close to its other end, and perhaps connected with it at shallow depth, there is a fifth neck, approximately half a mile across and crescentic in plan. In both necks the marginal, platy jointing, which is parallel to a steep flow banding, is roughly concentric, while the interior parts either show no banding at all or only an ill-defined fluxion that stands at high angles. Both necks consist of andesite essentially like that forming the necks near Agate Flat. One unusual feature, however, calls for attention. In the long, dike-like neck there is no porphyritic hornblende. Moreover the lava contains a small amount of deep green aegerite. As far as the writer is aware, this is the first noted occurrence of this mineral in any volcanic rock from the Cascade Range. The bulk of the andesite is composed of slender microliths of labradorite, intergranular opaque ore minerals, hypersthene, augite, and a little cristobalite. Cutting the rock at random are veinlets made up of aegerite, up to 0.4 of a millimeter long, radiating zeolites, and magnetite. For a distance of approximately 0.25 of a millimeter on either side of the veinlets, some aegerite has been produced by alteration of the other pyroxenes. Apparently one is dealing here with the effects of residual solutions rich in soda and iron that rose through the neck at a late stage (fig. 4*A*).

The sixth in the cluster of necks near Copco Dam adjoins the State Fish Hatchery; unlike the others it is composed of basalt. In plan, the

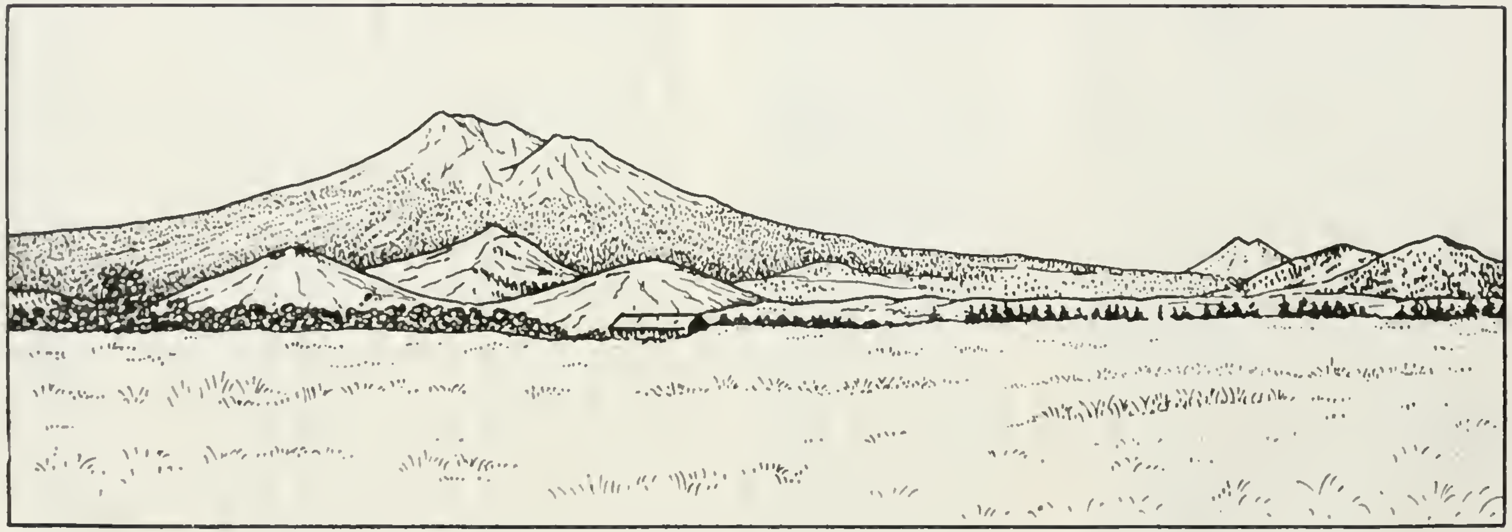

FIG. 5. View from near Little Shasta, looking south. In distance, from left to right, Mount Shasta, the parasitic cone of Shastina on its flank, and the hornblende andesite plug of Black Butte at its base. Of the three conical hills in front of Shasta, the central one is an andesitic neck, and the other two are rhyolitic protrusions in the Western Cascade series. The hills on the extreme right are also rhyolitic protrusions, part of a cluster around Drop-off Peak.

neck is oval, measuring approximately 350 yards in a north-south direction and 200 yards in maximum width. Cutting the massive basalt which makes up the bulk of the neck, are swarms of columnar dikes, mostly between 3 and 6 feet in width. Along the margins of the neck, and for a short distance inward from the southern edge, these dikes are arranged concentrically and either stand vertically or dip outward at angles of more than 60°, after the manner of ring dikes. In the core of the neck, on the other hand, the dikes trend northward or almost so, and all are vertical. Some dikes cross others at low angles, but most of them are parallel, multiple intrusions. No doubt the neck served as a feeder to a long succession of surface flows.

Under the microscope the basalt is seen to have a texture varying between intersertal and diabasic. Approximately 5 percent consists of golden-brown chlorophaeite, some of it developed from porphyritic olivine and some occurring in irregular patches throughout. Pale green, anhedral grains of diopsidic augite, up to 1 millimeter in diameter, total 30 percent of the volume; hypersthene is found only in the cores of a few of the larger augites, never as discrete crystals, and amounts only to 1 percent of the bulk. Roughly 55 percent of the basalt consists of basic labradorite laths up to 1 millimeter in length. Small, euhedral grains of magnetite (3 percent), and clear, buff-colored glass ($n = 1.525 \pm .002$) make up the rest.

Among the necks in Shasta Valley, the largest forms Gregory Mountain, on the outskirts of Montague, a short distance west of the Macdoel quadrangle. This consists of hornblende andesite. Another large neck rises from the flats near Cedar Lake (fig. 5). In plan, this one is oval, measuring a mile along the major and half a mile along the minor axis, and it rises to a height of approximately 750 feet. Throughout it is composed of massive, gray and olive-green, hornblende- and biotite-bearing pyroxene dacite, thoroughly propylitized by hydrothermal solutions. No flow-banding was observed within it, nor was any regular pattern of joints detected. A similar, almost structureless neck forms the hill known locally as the Camel, close to Little Shasta (fig. 6). This is made up of uniform, coarsely porphyritic, hornblende-rich pyroxene andesite. Unfortunately talus conceals its relations to the adjacent bodies of rhyolite, but almost certainly it represents another denuded filling of a volcanic pipe.

A high conical butte, referred to locally as Mary Peak and shown on the geologic map (pl. 1) as 3267 Hill, lies north of Snowdon. Its flanks are composed mainly of Umpqua sediments, but the top consists of fine-grained, black basalt. Where the basalt is columnar, the columns dip outward, locally at angles as low as 40°, suggesting that the cap is either the remnant of a flow that moved down a steep-sided valley in the Umpqua beds or the filling of a neck with inward-dipping sides. The presence of sporadic, small inclusions of milky quartz in the basalt favors the second view, for these can only have been picked up from Cretaceous conglomerates at depth. Perhaps the small patch of hydrothermally altered andesite on the northeast shoulder of the peak, and the patches of silicified and limonitized rhyolite on the opposite side also represent necks; if so, there must have been three closely spaced volcanoes in line, one of basalt, a second of andesite, and a third of rhyolite.

Two oval hillocks, each about 50 feet high, form islands in the flood of Recent basalt near Big Springs, in the eastern half of Shasta Valley. One is about 2,000 and the other 1,500 feet long. They consist of massive, unbanded, coarse-grained hypersthene andesite porphyry. The presumption is that these hillocks mark the feeding pipes of two more eroded volcanoes.

Dikes and Sills

Minor intrusions are surprisingly rare in the Macdoel quadrangle considering their abundance in the Yreka and Medford areas. Several vertical and steeply dipping dikes of olivine-bearing pyroxene andesite cut the coarse tuff-breccias on Sheep Rock. A vertical dike of andesite, with divergent, curving columns, cuts the lavas near Low Wood School, on the bank of Klamath River, and another columnar dike of andesite, trending N. 80° W. for almost a mile and dipping at angles of 20°-60° N., cuts the lavas near the northwest base of Eagle Rock Mountain. A 4-foot dike of andesite traverses the tuff-breccias above the artesian wells near the western foot of Miller Mountain, and, as mentioned already, there is a dike of rhyolite near Bogus School that probably served as a feeder for the eruption of welded tuff. These are the only minor intrusions seen among the Western Cascade series. Sills may be present between some of the flows, but none was surely identified.

Several steeply dipping to vertical dikes, a few inches to about a yard in width, cut the underlying Umpqua sediments between Willow School and the former site of Snowdon School, as well as on the Cooley Ranch, south of Mary Peak. But these intrusions are few and small compared with those to be seen farther north, in the valley between Hornbrook and Hilt (see pl. 4). Most of these intrusions are sills rather than dikes, and they range in composition from dacite porphyry to basalt porphyry, the commonest ones being propylitized augite- and hypersthene-andesite porphyries. Some in the Medford quadrangle show a density stratification, a lower gabbroid facies passing upward into diorite, as discussed by Merriam.[21] Wells and Waters [22] have described basic intrusions in the Blackbutte-Elkhead-Nonpareil area in Oregon, some of which they consider to have been feeders to basaltic flows in Umpqua formation.

Age and Mode of Deposition of the Western Cascade Series

Elsewhere the writer [23] has summarized the available evidence relating to the age of the Western Cascade series, concluding that the beds range from upper Eocene to the top of the Miocene. Volcanism had already begun in the Roseburg and Medford areas during middle Eocene (Umpqua) time, and some tuff is present in the upper part of the Umpqua formation in the Yreka quadrangle. During upper Eocene time, volcanism became more widespread, and vents became active in the Macdoel region.

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[21] Merriam, Richard, Magmatic differentiation in gabbro sills near Ashland, Oregon: Am. Jour. Sci., vol. 243, pp. 456-465, 1945.

[22] Wells, F. G., and Waters, A. C., Basaltic rocks in the Umpqua formation: Geol. Soc. America Bull., vol. 46, pp. 961-972, 1935.

[23] Williams, Howel, The geology of Crater Lake National Park, Oregon: Carnegie Inst. Washington, Pub. 540, 1942. . . . The ancient volcanoes of Oregon: Condon Lecture, Pub. 1, Oregon State System of Higher Education, 1948.

Among the tuffs forming the lowermost 40 feet of the Western Cascade series near Hornbrook, petrified wood and fossil leaves are plentiful, and these, according to Chaney,[24] indicate an upper Eocene or Oligocene age. Abundant petrified wood is also present among the tuffs in the Macdoel quadrangle, but no leaves have yet been found there. There is no reason to doubt, however, that the lowermost volcanic rocks are equivalent to the leaf-bearing tuffs near Hornbrook.

Chaney's analysis[25] of the Western Cascade floras shows that during late Eocene time, mild and humid, semitropical conditions prevailed. Avocados, cinnamons, figs, and persimmons flourished in the lowlands, while on the higher hills and cones more temperate forests grew, rich in redwood, alder, tan oak, and elm. A mild and humid climate also prevailed during the Oligocene period. Even far inland, beyond the Cascade Range, the conditions were uniform, so that redwoods remained predominant in the forests. Nearer the coast, in sheltered bays, warm temperate and subtropical forms persisted. By the end of Miocene time, writes Chaney, the forests were "like those of today in the valleys of Michigan and Ohio, in the Redwood Belt of California; they were essentially like those which had lived in the uplands during the Eocene." The occurrence of fossil redwoods east of the Cascade Range in late Miocene beds indicates that the range was still not high enough to check moisture-bearing, ocean winds and thus to reduce the rainfall on the lee side by more than a few inches. And this despite the fact that lavas and pyroclastic ejecta had accumulated to a thickness of more than 10,000 feet. The conclusion is inescapable: the area now occupied by the Western Cascade series must have subsided many thousands of feet as the volcanic eruptions continued. From top to bottom of the series, there is no evidence of deep erosion during accumulation. All signs suggest that the lavas and tuffs were laid down on a surface of low relief. Beds of conglomerate are found chiefly near the base of the series; at higher horizons, the interbedded sediments consist principally of tuffaceous shales and rare seams of lignitic coal such as would be formed in bogs and on alluvial flats. The absence of any marked angular unconformities between the volcanic rocks also indicates that the topography was one of gentle relief. If high cones existed they must have lain to the east of the present outcrop of the Western Cascade series, and their remains must now be buried beneath the younger lavas of the High Cascades.

Surprisingly few volcanic necks have been discovered in the Western Cascades considering the great volume of erupted material. Indeed they are more numerous in the Macdoel quadrangle than in any other part of the belt. Considering also the scarcity of Tertiary intrusions among the bedrocks of the Klamath-Siskiyou Mountains, it can only be supposed that most of the Western Cascade volcanoes lay far to the east. Many flows may have been erupted from fissures rather than from cones; in such event the chances of locating their sources are much reduced.

Earth Movements at the Close of the Miocene Epoch

Reference has already been made to Wells' discovery of a pronounced angular discordance between the Umpqua formation and the

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[24] Personal communication.

[25] Chaney, R. W., Ancient forests of Oregon: Carnegie Inst. Washington, Pub. 501, Cooperation in Research, 1938.

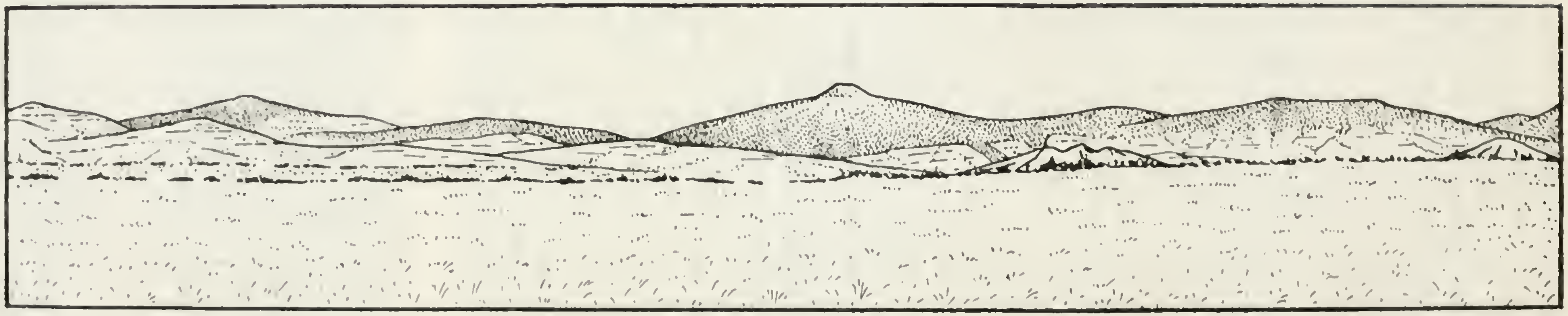

FIG. 6. View from 2 miles west of Little Shasta, looking east. Wooded volcanoes of the High Cascades in distance; from left to right, the Willow Creek Mountain andesitic volcano (first two peaks), the Recent cone of Goosenest (near center), an unnamed shield volcano, then the Miller Mountain shield, and finally part of the Whaleback basalt cone. In front of the High Cascades are grass-covered hills composed of the Western Cascade series, locally showing bedding. The hill with three peaks, in middle distance, is an andesitic neck, known as "The Camel"; to its right, near edge of picture, is a rhyolite dome in the Western Cascade series.

earliest of the Western Cascade lavas in the Medford quadrangle. This implies tilting in late-middle or upper Eocene time. Evidence has also been presented to indicate a gradual, large-scale subsidence of the Western Cascade series during accumulation. Presumably this subsidence was most marked in the vicinity of the parent volcanoes, that is near and under the present High Cascades. At the same time, the bedrock area of the Klamath-Siskiyou Mountains was slowly rising as it was eroded. Such a coupling movement accounts for the easterly and northeasterly dips of the Western Cascade series and for the diminution in the angle of dip in those directions.

At the close of the Miocene epoch, the entire Cascade belt was greatly upheaved; it was then, for the first time, that the country to the east was deprived of sufficient rainfall to permit continued growth of redwood forests. This upheaval was accompanied by the formation of several faults trending slightly west of north, and by the opening of north-trending fissures along and near the crest of the range. It was from these fissures that the Pliocene and younger lavas were erupted to build the giant cones of the High Cascades.

High Cascade Series: Pliocene to Recent

Plio-Pleistocene Volcanoes

Basaltic Shield Volcanoes

Throughout the southern part of the High Cascades in Oregon and California, Pliocene and early Pleistocene times were characterized by the growth of a north-south chain of large, flattish shield volcanoes built by quiet effusions of fluid olivine basalt and basaltic andesite. Great diversity had marked the behavior and products of the volcanoes that produced the Western Cascade series; on the contrary, the volcanoes now to be described were extremely uniform in their activity; fragmental explosions seldom interrupted the quiet outflow of lava, and the flows themselves varied only slightly in composition despite their wide extent.

The principal Plio-Pleistocene basaltic volcanoes of the Macdoel quadrangle are Miller Mountain, the partly buried shields under the lavas of Willow Creek Mountain and the Goosenest, Ball Mountain, Eagle Rock Mountain, McGavin Peak, and Secret Spring Mountain. East of these, along the edge of Butte Valley, there are several coeval basaltic volcanoes, much modified by faulting, that form part of the well-known block-fault country extending northward into the Klamath Falls region.

There is no certainty as to the precise order in which these coalescing volcanoes began to grow; most of them were active simultaneously for a long period. Probably the southernmost, Miller Mountain, which is the most deeply eroded, was the first to become extinct. The flanks of some, such as Ball Mountain, Ikes Peak, and the Eagle Rock volcano are so little dissected that their final eruptions may not date back further than late Pleistocene time.

Although patches of red scoria, the relics of former summit cones, cap Ball Mountain and the peak to the south, and may also be seen near the top of the basaltic shield north of Copco Dam, the craters of all the Plio-Pleistocene basaltic volcanoes have been destroyed by erosion. Nevertheless, because none of the volcanoes was ever glaciated, they are much less denuded than coeval shields in the High Cascades of Oregon, many of which have been dissected sufficiently to reveal the fillings of their central conduits. It is chiefly around their margins that the Macdoel shields have suffered denudation, for the flanks have been driven backward by the sapping action of springs and streams that cut readily into the less resistant rocks of the underlying Western Cascade series. This process accounts, for example, for the abrupt termination of the lavas of the Eagle Rock volcano along the rims of the canyons of the Klamath River and of Bogus and Shovel Creeks. It accounts also for the large amphitheater on the north side of Secret Spring Mountain and for the huge embayment cut into the western flank of the Miller Mountain shield.

Where least modified by faulting and erosion, the basaltic shields have much gentler slopes than those of the adjacent andesitic volcanoes. For instance, the Eagle Rock shield has slopes that range from 5° to 7°, whereas the neighboring andesitic cone of Willow Creek Mountain has slopes of 10° to 13°.

A glance at the geologic map (pl. 1) will show that most of the basaltic shields are oval in plan rather than circular. Thus the Eagle Rock shield is elongated in a north-south direction, while the Ball Mountain, Miller Mountain, and Mount Hebron volcanoes are elongated in directions between northwest and N. 30° W. These elongations, coupled with alinement of the shields themselves, suggest growth over a major set of north-south fissures and a minor set inclined at angles of 30°-45°, and it is noteworthy that these are also the directions of the younger fault scarps that border Butte Valley.

The eastern shields never extended much farther than at present, but the larger, western shields, such as the Eagle Rock volcano, which still covers 60 square miles, the Miller Mountain volcano, and the two shields under the Goosenest and Willow Creek Mountain must formerly have been much more extensive, for remnants of their flows spread far down the valley of the Klamath River and into Shasta Valley. Before any of the shields began to develop, a north-trending ridge of Western Cascade rocks already existed, roughly coincident with the line of the present High Cascades. On the west this ridge rose 3,000 to 4,000 feet above Shasta Valley; on the other side, it was probably much lower. The drainage at that time was mostly toward the west, and the Klamath River already flowed in that direction through a broad and shallow valley. Evidence for the old drainage lines may be seen in the distribution of the outliers of basaltic lava. For example, the patches of basalt near Bogus School are relics of a flow from the Eagle Rock volcano that poured westward down a steep-sided, boulder-strewn valley, and the patches perched on the walls of the Klamath River clearly indicate the form of an ancient channel. More striking are the outliers of basalt related to the shield volcano beneath Willow Creek Mountain. Four residual caps rest on the spur between Dewey Gulch and Dry Creek, at elevations of 4,000 to 4,500 feet. Two miles to the southwest, a fifth outlier forms Solomon's Temple, at an elevation of approximately 3,900 feet. West of this are two more outliers forming Table Rock, at elevations of between 3,550 and 3,700 feet, that rest on coarse fluviatile conglomerates charged with boulders of quartzite. Taken together these seven outliers mark the course of an old stream-channel trending southwestward into the ancestral Shasta Valley. At Table Rock two successive flows followed the channel. Other basaltic flows spread westward into the ancestral Shasta Valley from the Miller Mountain volcano.

Lithology. By far the dominant lava of all the shields is a massive, pale gray, microvesicular, holocrystalline basalt liberally sprinkled with granules of olivine. Flows that contain a little glass are generally darker and more coarsely vesicular, while the glass-rich tops and bottoms of a few flows are black and scoriaceous. Most of the flows vary in thickness between 10 and 50 feet; exceptionally they reach a thickness of 100 feet. Few are auto-brecciated and the crusts of most are smooth. In many places, particularly along the rims of the Klamath River, Bogus and Shovel Creek canyons, columnar jointing is well developed. The two valley-filling flows of Table Rock show coarse columnar jointing in their upper parts, while toward the base they exhibit a platy jointing that curves upward from the horizontal to the vertical. In addition they are cut by throughgoing vertical joints alined parallel to the direction of flow and showing horizontal mullion structure. Both the platy and the longitudinal joints are to be ascribed to shearing of the lava as the marginal and basal portions, owing to greater viscosity, were impeded in their advance relative to the more fluid, interior parts.

Save for the relics of summit scoria cones already mentioned, there is little trace of explosive activity on any of the shields. Thin beds of reddish cinders separate some of the flows of the Secret Spring Mountain volcano, but elsewhere no fragmental layers were observed between the lavas. Nor were any interbeds of diatomite detected, such as are common between the basaltic flows of coeval shields in the vicinity of Klamath Falls.

Petrography. The typical lava of the shield volcanoes is a fluidal, intergranular, olivine-augite basalt. The volume percentage of olivine phenocrysts varies between 2 and 10. In some flows the mineral is fresh; in others it is partly altered to iddingsite, or, less commonly, to bowlingite. Normally this alteration is confined to the margins of the crystals, but in some of the Ball Mountain lavas the rims of the olivines are fresh while the cores are replaced by iddingsite, suggesting that oxidation and enrichment in iron took place at an early stage of consolidation. Occasionally, and particularly in scoriaceous basalts reddened by fumarolic action, the olivine crystals are partly converted to magnetite and hematite.

Augite forms phenocrysts only in a few flows, chiefly among those of the eastern shields. Rarely it forms ophitic plates partly enclosing the feldspars. Characteristically, however, the mineral occurs as minute anhedral grains in the dense groundmass, and it varies in amount between 25 and 35 percent of the bulk. It is a pale green, diopsidic variety with optic angles of approximately 50°-55°. Minute prisms of hypersthene are present in most flows, but only in very minor amount.

Phenocrysts of plagioclase are exceptional, although in some lavas, as on McGavin Peak, sporadic crystals of bytownite reach 1 millimeter in length. Typically the feldspar occurs in subparallel microliths less than half as long. In composition these range from medium labradorite to acid bytownite.

Where present, interstitial glass composes no more than 5 percent of the volume, and its color varies from dark brown to black according to the content of finely divided magnetite. A little cristobalite and/or

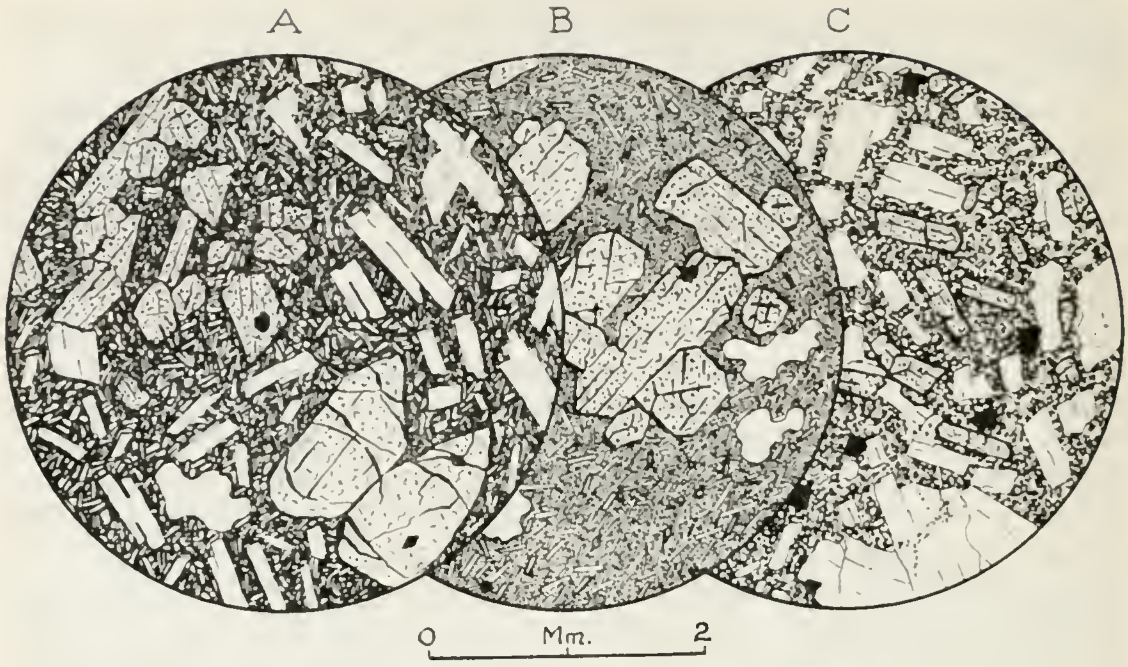

FIG. 7. Microdrawings showing lavas of the High Cascades. *A*, Olivine-bearing hypersthene andesite (51) from halfway up the north flank of the Goosenest volcano. Phenocrysts of olivine, hypersthene, and labradorite, in a matrix of brownish-black glass charged with sodic labradorite microliths and grains of pyroxene. *B*, Pyroxene andesite (518) from the youngest flow of Shastina, on U. S. Highway 97, near B.M. 3471. Phenocrysts of augite and hypersthene; groundmass of medium labradorite laths, pyroxene grains (chiefly hypersthene), opaque ore minerals, and interstitial glass. *C*, Pyroxene andesite (59) from summit of Willow Creek Mountain cone. Phenocrysts of hypersthene and augite, the former predominating, together with labradorite, in a groundmass of microlithic feldspar, specks of pyroxene and opaque ore minerals, and a little tridymite.

tridymite is almost invariably present, with or without opal, lining cracks and the walls of vesicles, and some fumarolic hematite is associated with these late crystallizing silica minerals. However, hydrothermal alteration, such as that common among the lavas of the Western Cascade series, is completely lacking.

It is possible that some of the flows composing the shield volcanoes are basaltic andesites rather than true basalts, but only numerous chemical analyses would decide the question.

Basaltic Intrusions

At two localities the Western Cascade series is cut by dikes of columnar basalt that represent feeders of some of the flows just described. One of these localities is Temple Rock, a short distance east of the lava-cap of Solomon's Temple. Here is a steep-walled crag, approximately 250 feet high, elongated in a northeastern direction for about 250 yards, consisting of six parallel, vertical dikes of basalt. The rock is finer grained than any of the surface flows and is made up of the following constituents: acicular prisms of augite (20 percent), specks of opaque ore minerals (20 percent), and laths of basic labradorite (55 percent), none of which exceed even 0.1 of a millimeter in dimension, together with small phenocrysts of fresh olivine up to 0.5 of a millimeter across ($2V = 85°$, positive).

The other dike-feeder lies 3 miles to the south-southeast. There also the intrusions trend northeastward, and they consist of similar, fine-grained basalt. Presumably they represent the fillings of fissures on the flanks of the original shield volcanoes.

Hornblende-Bearing Andesites and Dacites (?)

Close to the southeast corner of the Macdoel quadrangle, bordering Butte and Alder Creek valleys, is a thick succession of coarsely porphyritic, pale gray to pink, hornblende-bearing flows of pyroxene andesite and dacite (?) characterized by abundant glass and much interstitial cristobalite. Locally these flows are almost pumiceous; all are extremely brittle so that they crumble when struck with a hammer. Individual flows measure several hundreds of feet in thickness, and on the wall of Alder Creek canyon their aggregate thickness exceeds 2,000 feet. All must have been distinctly viscous, and indeed the last extrusions piled over the vents to form domical mounds, such as Hills 6245 and 5653 (see geologic map, pl. 1). All represent flank flows of the Haight Mountain volcano, the summit of which lies to the south of the quadrangle.

As to their age, they appear to interfinger with pyroxene andesite flows which overlie olivine basalts in the canyon of Butte Creek. Hence they are younger than some of the High Cascade shield volcanoes. On the other hand, they have been deeply dissected by the glaciers that formerly filled the valleys of Butte and Alder Creeks, and they must therefore be older than the basalts of such little modified shields as Ball Mountain and Eagle Rock.

Petrography. A typical sample of lava from the east wall of Butte Creek canyon, opposite Granada Ranch, has the following content: phenocrysts of feldspar, up to 4 millimeters long, showing strong oscillatory zoning and a range in composition from acid labradorite to medium andesine, 40 percent; subhedral prisms of strongly pleochroic hypersthene, between 0.1 and 0.5 of a millimeter long, and optic angles of 65°-70°, 4 percent; oxyhornblende crystals, up to 2.5 millimeters long, (pleochroic from yellowish green or yellow to deep russet, Z to c, 0° to 5°, 2 V. = 75°, negative), 2 percent; glassy groundmass rich in microlithic oligoclase and dusty ore, 54 percent. The refractive index of the glass, 1.520 ± .002, indicates a silica content of 63 percent.

A second sample, from the same wall of the canyon, about 1½ miles to the south, differs from the preceding chiefly in having a cryptofelsitic instead of a glassy groundmass, and also in the presence of tridymite (5 percent) and cristobalite (2 percent). A third sample, taken 1½ miles still farther south, carries phenocrysts of basic andesine (40 percent), hypersthene (8 percent), oxyhornblende (2 percent), and augite (1 percent) in a pilotaxitic groundmass made up of oligoclase and granular black ore minerals. This lava is noteworthy on account of the oxidation not only of the hornblende, which is largely converted to ore, but also of the hypersthene which has a patchy brown color and is flecked with hematite and rimmed with magnetite.

A peculiar type of lava outcrops at the northern base of Haight Mountain, approximately 2 miles east of the Double Spring in Butte Creek valley. In this, phenocrysts of zoned plagioclase (acid labradorite-basic andesine), up to 3 millimeters long, make up 30 percent of the bulk. Dark yellow to russet oxyhornblendes, up to 4 millimeters long, total 4 percent; hypersthene, 3 percent; augite, 1 percent; olivine, 1 percent, and reddish-brown biotite with sagenite webs, 1 percent. No other lava in the region shows such a wide variety of ferromagnesian phenocrysts. They lie in a dense, pilotaxitic matrix consisting of acid andesine with interstitial ore and cryptofelsite stippled with cristobalite.

In default of chemical analyses, it is believed that most of the lavas just described from the Haight Mountain volcano are dacites, although some may be siliceous andesites.

Pyroxene Andesite Lavas

The headwaters of Butte and Alder Creeks lie among glaciated flows of pale gray, coarsely porphyritic pyroxene andesite which, as mentioned already, are coeval with some of the Haight Mountain dacites and hornblende-bearing andesites.

Lavas of approximately the same age and composition form the steep-sided volcano of Willow Creek Mountain. These are marked by abundant phenocrysts of hypersthene, augite, and labradorite in a pilotaxitic base containing a little tridymite and cristobalite lining cavities. They resemble the principal types of andesite composing such other High Cascade cones as Mounts Shasta, Mazama, and Rainer. Close to the top of Willow Creek Mountain the flows are interbedded with tuff-breccias, but there is no trace either of a summit cinder cone or of the original crater.

Along its western side, the andesite cone rests partly on the Western Cascade series and partly on olivine basalts belonging to the High Cascade series. The distribution and attitudes of the latter suggest that a shield volcano underlies the andesite cone and that it was already much eroded before the andesitic eruptions began. Along the opposite side, the lavas of Willow Creek Mountain probably interfinger with the olivine basalts of the Ball Mountain shield.

A prominent mass of pyroxene andesite projects from the northeast flank of Miller Mountain. It is surrounded and in part overlain by the basaltic flows of that shield volcano, and appears to be a domical protrusion of the Lassen Peak type. No definite internal structures can be seen and the sides are heavily mantled by talus, possibly formed as the dome was growing.

The principal activity that built Mount Shasta took place during Pleistocene time, and the volcano had practically reached its maximum height before the close of the Wisconsin glaciation. At that time, glaciers spread down the northwest side of the mountain into Shasta Valley, reaching as far as the Dwinnell Dam, at an elevation of approximately 2,800 feet. Since the ice began to retreat from this position, there have been many eruptions of lava from Shasta. Numerous flows discharged from fissures high on the flanks of the mountain therefore show the effects of glaciation, even though from a chronological standpoint they must be classed as post-Pleistocene. Other flows of Recent age are covered by glacial debris in their upper parts and are bare near their snouts. The difficulty in deciding whether certain of the Shasta flows are Pleistocene or Recent is aggravated by the fact that widespread sheets of fluvioglacial outwash mantle them. Some of this outwash undoubtedly dates back to Pleistocene time, but it has been accumulating ever since. Among the Shasta flows that extend into the Macdoel quadrangle and are probably of Pleistocene age are the black, glassy, pyroxene andesites north of Yellow Butte.

Recent Eruptions

The Recent eruptions include all lavas discharged since the Shasta glaciers began to retreat at the close of the Wisconsin stage of the Pleistocene. They comprise flows and associated cones hardly modified by erosion, some of which are so fresh that they must have been formed within the last milennium or two. The exact order of formation is uncertain, and no doubt some volcanoes were active simultaneously. In the following notes they are described as nearly as possible in chronological order.

Deer Mountain Volcano

Deer Mountain consists of five lava cones built over two approximately north-trending fissures. Four of these cones are flattish shields, three composed of dark, vesicular, glass-rich pyroxene andesite, and the other or southernmost composed of vesicular olivine basalt. The fifth cone, which forms the summit of the mountain, is a steeper pile of pyroxene andesite. No craters are to be seen; either they have been destroyed by erosion or they were filled by the final effusions. All five cones are heavily mantled with basaltic cinders blown from nearby vents and all are lightly veneered with pumice blown from Mount Shasta in 1786.

The basalts of the southernmost cone are devoid of porphyritic feldspar but carry abundant crystals of olivine up to 2 millimeters across; the andesites of the other cones are all rich in large phenocrysts of both pyroxene and plagioclase, but carry little or no olivine. They may be classed as hypersthene-rich, hyalopilitic andesites. In most specimens phenocrysts of hypersthene, occasionally with jackets of augite, constitute between 5 and 8 percent of the bulk, but porphyritic augite is either absent or makes up no more than 2 percent. Microgranules of augite are equally scarce, and olivine nowhere exceeds 1 percent of the volume. Phenocrysts of zoned acid bytownite-basic labradorite, up to 2 millimeters long, together with microliths of medium labradorite total between 50 and 55 percent of typical specimens. Ore-charged, brownish-black glass constitutes about a third of the bulk, and some flows show minute crystals of cristobalite lining cavities. Among other Recent lavas of the quadrangle, the ones that most closely resemble the Deer Mountain andesites are those of the Goosenest volcano.

Eruptions Near the Base of Mount Shasta

A wide area of blocky to scoriaceous pyroxene andesite occurs in the vicinity of Bolam and Yellow Butte. As far north as a line roughly midway between the Southern Pacific Railroad and U. S. Highway 97, the hummocky surface of these flows is patchily covered by glacial moraines. But farther north the same flows show no signs of having been covered by ice, although they are partly covered with fluvioglacial debris. Hence it is concluded that they were erupted during an early stage in the main retreat of the Shasta glaciers.

Close to their snouts some of these flows eddied around the flat-topped, steep-sided Haystack Butte. This consists of pale pink, thoroughly oxidized hornblende andesite, and is apparently a domical protrusion. Near the northern foot of this butte there is a thick flow of similar hornblende andesite capped by a small cinder cone. Both the flow and cone are older than Haystack Butte since the latter shows no cover of cindery ejecta.

Whaleback Volcano

The largest of the Recent volcanoes in the Macdoel quadrangle is the Whaleback, an imposing, steep cone that rises 3,000 to 4,000 feet above the surrounding country. It is composed almost entirely of dark, vesicular flows of basalt, usually devoid of porphyritic feldspar but with 4 to 6 percent of olivine phenocrysts and, especially on the western flank of the volcano, abundant crystals of diopsidic augite (2V — 55°; Z to c — 56°) up to 3 millimeters in length. In flows devoid of augite, hypersthene is usually present in minor amount. Sub-parallel microliths of basic labradorite average about 40 percent of most specimens. All these constituents lie in a base of opaque black glass, constituting another 40 percent by volume.

On the summit of the main lava cone there are two lava-scoria mounds on a north-south line, the larger of which exceeds 500 feet in height and has a well-preserved crater. On the eastern flank there is a third mound of lava and scoria, apparently without a crater. Erosion has scarcely modified the form of the Whaleback and the flows nowhere show traces of having been glaciated.

Kegg, Soule Ranch, and Horsethief Butte Cones

The precise position of these cones in the sequence of Recent eruptions is uncertain, although all are older than the Little Deer Mountain volcano.

The Kegg cone, on the eastern edge of the quadrangle, has been almost wholly removed by quarrying. It consists of red and black, basaltic cinders crowded with lapilli and bombs, some of which measure 4 feet across. The quaquaversal dips of these ejecta indicate that originally the cone was a low, oval mound, the vent of which lay near the center of the quarry. A few irregular stringers of basalt cut the cinders; these probably are fillings of fissures through which short flows of lava escaped to the surface.

Approximately 3 miles to the southwest, near the Soule Ranch, there is another cinder cone almost eviscerated by quarrying. Here the ejecta are composed for the most part of red scoriaceous lumps between half an inch and a yard across. Above the well-stratified cinders lie patches of agglutinate formed by fragments that were pasty enough when they landed from flight to adhere to each other. As in the Kegg cone, the vent of this one also lies close to the center of the quarry. A stumpy flow of olivine basalt issued from the foot of the cone on the south side. The lower flanks of the cone are covered to a depth of a few feet by bouldery, fluvioglacial outwash.

Equidistant from the two cones just described are two others that coalesce to form Horsethief Butte. Both are made up of olivine basalt scoria. Whether or not they were built before the adjacent fault scarps were formed is uncertain owing to slides of talus.

Pluto's Cave Basalt

The eastern half of Shasta Valley is occupied by a sheet of olivine basalt referred to here as the Pluto's Cave flow, after the large lava tube near its southern end, at the locality named The Caves on the geologic map, plate 1. This flow covers more than 50 square miles and exceeds 20 miles in length. It is thus by far the largest flow of any age in the Macdoel quadrangle. It seems to have issued from fissures close to the northeast base of Mount Shasta.

For the first 5 miles, as far as the Southern Pacific Railroad, the surface of the flow has an inclination of 5° ; for the next 5 miles, to Pluto's Cave, the slope diminishes to 3° ; then, for another 5 miles, it diminishes to approximately 1°, finally becoming almost horizontal.

Evidence concerning the thickness of the flow is meager. Before the lava was erupted, the eastern half of Shasta Valley was a broad depression containing hillocks of andesite like those to be seen in the western half. A few of these hillocks still rise as islands within the flood of basalt. Almost certainly the Shasta River and Parks Creek flowed through this depression before being diverted to their present channels by the outflow of lava. In part the depression was floored by dark volcanic sand, for Mr. C. B. Kay reports an outpouring of such material from an artesian well sunk through the basalt. The thickest portion of the flow is undoubtedly the median part that extends northwestward through Pluto's Cave, for here the lava is piled into a high ridge elongated parallel to the direction of flow. A short distance to the north of the cave, according to Mr. Kay, basalt was cut to a depth of approximately 290 feet in a well, and it may be that locally the lava attains a thickness of 400 feet. Beyond the Big Springs road the thickness diminishes rapidly, until in Little Shasta Valley it is reduced to a few tens of feet. The narrow ribbon that spread into the Shasta River must also be extremely thin.

Not only did the lava force Shasta River and Parks Creek into new channels, but it deranged the drainage elsewhere. South of the Big Springs road the marginal parts have been largely covered by fluvioglacial outwash from the slopes of Mount Shasta, as well as by cinders blown from younger cinder cones. Large fans of pebbly and sandy outwash are now spreading over the edge of the lava east of Dwinnell Reservoir, and the finer materials in them are being winnowed by the winds to form dunes in the vicinity of Pluto's Cave.

The main topographic features of the basalt are the median ridge in its upper, constricted part, the caves or lava tubes in the same area, the schollendomes or oval mounds formed by hydrostatic pressure of liquid lava under the congealed crust, the pressure-ridges along the margins and the collapse-depressions in the lower part of the flow.

Of the lava tubes, the largest is Pluto's Cave itself. It was discovered in 1863, and, according to Wells,[26] the "succession of halls and caverns" can be traced for a distance of between one and a half and two miles. Today it is doubtful if it can be followed for more than half a mile. It trends approximately northwestward, lying close to and parallel to the axis of the flow. In several places the roof has collapsed so that entry is easy. Most of the tube has a diameter of 30 to 50 feet, but the floor is thickly covered by debris fallen from the ceiling and by sand blown from the dunes on the surface. Locally the diameter reaches 80 feet. The walls reveal three, and in places four superimposed flows with clinkery tops and bottoms. These do not represent distinct effusions separated by intervals

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[26] Wells, H. L., History of Siskiyou County, Oakland, 1881.

of quiet, but simply "flow-units" or lobes extruded through the front of the advancing lava.[27] No lava stalactites hang from the ceiling, and only crude strand lines were left on the walls by the ebbing of the liquid interior as it drained to lower levels.

Oval schollendomes, a few feet to 20 feet high, are scattered at random over the surface of the lower half of the flow. Marginal pressure ridges, many of which have gaping fissures on their crests, are most numerous along the eastern edge, as in the vicinity of the Hart Ranch. Collapse depressions are distributed sporadically over the flow, but especially near the margins of the lower part. Some are elongated trenches bordered by low cliffs, like the one near the eastern foot of Drop-off. Others are approximately circular, like the one close to and almost in line with Pluto's Cave. Still others are irregular in outline, and many are occupied by ponds and marshes. The majority were formed by collapse of lava-crusts over tubes emptied by drainage, but some are being produced today while others are being deepened by removal of sand and gravel from beneath the lava by subterranean streams.

Lithologically, the basalt is quite uniform. All of it is black, vesicular, olivine-rich augite basalt with a fairly smooth crust marked by gentle swells and hollows. Pahoehoe skins are exceptional. A description of the microscopic features of two samples will suffice. One of these, typical of the crust of the basalt, has a hyalopilitic texture and consists of the following: olivine crystals, up to 1 millimeter in length, 12 percent; laths of basic labradorite, also measuring up to 1 millimeter long, 50 percent; minute, anhedral grains of augite, 2 percent; interstitial black glass, 15 percent; and amygdules filled with radiating calcite and a little opal, 21 percent. The other sample is representative of the holocrystalline lava beneath the glassy crust. In this, olivine makes up 5 percent of the volume, whereas small prisms and anhedral grains of augite total approximately 25 percent. Laths of basic labradorite, composing 60 percent of the bulk, are much smaller than in the glassy basalt, few measuring more than 0.2 of a millimeter in maximum dimension. Granular opaque ore minerals account for 8 percent of the whole, and interstitial cristobalite makes up the remainder.

Butte Valley Basalt

The southern end of Butte Valley, around Jerome, is occupied by an almost horizontal sheet of black, vesicular olivine basalt dotted with schollendomes, almost identical in appearance with the Pluto's Cave lava just described. Its visible extent in the Macdoel quadrangle is shown on the geologic map, plate 1, but it extends far to the east, and probably to the north also beneath a cover of alluvium. How far to the north the basalt spread is uncertain. Several wells near Macdoel, after passing through 30 to 50 feet of sediment enter basalt, although this may be of Pleistocene age rather than Recent. But that the Butte Valley basalt did extend as far as Mount Hebron Station seems likely because a well at that locality passed through 47 feet of basalt, beginning at a depth of 30 feet, before continuing through 24 feet of cinders and then cutting clay, sand, and gravel for another 113 feet. Since no sediments are present in the Plio-Pleistocene succession, the inference seems justified that

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[27] Nichols, R. L., Flow-units in basalt: Jour. Geology, vol. 44, pp. 617-630, 1936.

the basaltic lava here is of Recent origin. At Juniper Lodge, which lies at the bottom of the Mount Hebron grade on U. S. Highway 97, the Butte Valley basalt is 80 feet thick and underlain by dark volcanic sand.

Similar basalts, probably of about the same age, are widely exposed near Bray. Their source, like that of the Butte Valley lava, lies in fissures east of the Macdoel quadrangle.

Little Deer Mountain Volcano

The upper part of Little Deer Mountain is a cone of red, brown, and black cinders between 500 and 600 feet high, breached on the south side. Surrounding it is a field of Recent lava more than 10 square miles in extent. Judging by the thickness of the cinder cover, most of the lavas were erupted during the waning stages of the explosive activity that built the cone. Indeed some of the lava close to the northern base of the cone was extruded after the fragmental explosions had come to an end.

The first flows spread eastward beyond Penoyar for about 5 miles. These are thin sheets of black, vesicular olivine-augite basalt with smooth to gently undulating crusts dotted with sporadic schollendomes. In texture and mineral content they resemble the Pluto's Cave basalt. Most of the flows are concealed by a mantle of fine ash, and close to their snouts they are also covered by sandy outwash from the adjacent hills of fluvioglacial debris.

The principal flows were then discharged, accumulating to a depth of 500 feet. Most of these issued from the breach on the south side of the cone, but some escaped from vents on the opposite side. Being more viscous than the earlier flows they only spread half as far and all terminated with steep, blocky fronts. Their rough surfaces are marked by high crags and pinnacles and by irregular channels dividing branching ridges, and their scoriaceous, clinkery interiors are strongly autobrecciated. Locally they are thoroughly reddened by fumarolic vapors, but normally their colors range from dark gray to black as the content of interstitial glass increases. Like the first flows, they are rich in phenocrysts of olivine but contain only sparse phenocrysts of plagioclase. Porphyritic augite is lacking, but the mineral is abundant as minute granules between the microliths of labradorite in the groundmass.

The final gush of lava, which issued from the north base of the cone, is much less extensive, and consists, not of olivine basalt but of olivine-free, pyroxene andesite or basaltic andesite. Approximately 40 percent of the lava consists of opaque, black glass; about 50 percent is composed of basic labradorite microliths, while the remainder is made up of phenocrysts of hypersthene and augite up to 1 millimeter in length.

Butte Creek Basalt

From a fissure at an elevation of approximately 6,000 feet on the east wall of Butte Creek canyon, a narrow flow of black, vesicular olivine basalt poured for a distance of 10 miles, ending close to the Soule Ranch at an elevation of about 4,800 feet. A mound of scoriaceous lava marks the source. In the upper part of the canyon, the flow is almost completely covered by lush meadows and marshes; in the lower part it is largely concealed by fluvioglacial outwash and cinders. A few schollendomes rise above the cover near Mount Shasta Woods, but the best exposures

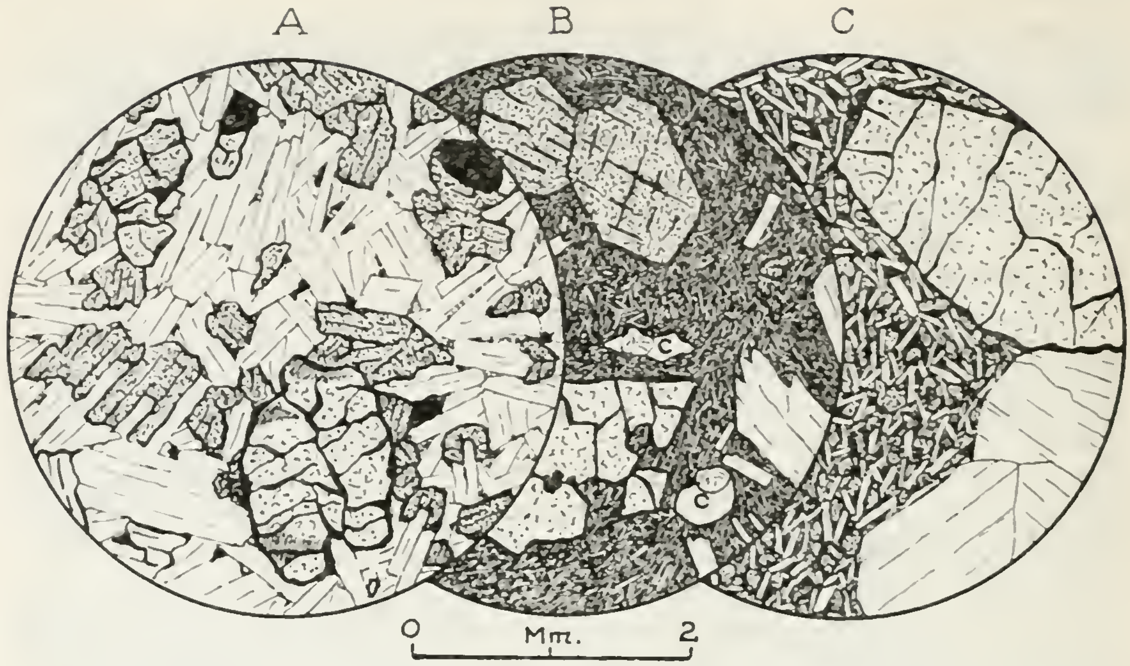

Fig. 8. Microdrawings showing lavas of the High Cascades. *A*. Coarse-grained augite-olivine basalt (26) from summit of Herd Peak. Laths of sodic bytownite-calcic labradorite, grains of greenish diopsidic augite, and phenocrysts of olivine, partly altered to hematite, with a little interstitial tridymite and cryptofelsite. *B*. Porphyritic olivine-augite basalt (591) from Recent flow in Alder Creek canyon. Fresh phenocrysts of diopsidic augite, olivine, and sodic bytownite in a dense base of microlithic labradorite, intergranular pyroxene, and opaque ore minerals. Round grains of cristobalite (C) in cavities. *C*. Coarsely porphyritic olivine-augite basalt (166) from Recent flow near Copco Dam, Klamath River. Large phenocrysts of olivine and bytownite-anorthite in a groundmass composed of labradorite-bytownite laths, granular augite, and opaque ore minerals.

of the basalt are to be seen below that point, where Butte Creek has incised a youthful gorge between the eastern margin of the flow and the adjoining moraine. In this part of its course the lava varies in thickness between 10 and 150 feet. Most of it moved down the canyon through tubes beneath a smooth to gently undulating crust. Around Mount Shasta Woods and on the Granada Ranch, copious springs of cold water now issue from the evacuated channels. Until Butte Creek established a new course along the edge of the flow, the lava must have been inundated by sheet-floods, and it is to these that one can ascribe the cover of sediment.

Under the microscope, the basalt closely resembles the Pluto's Cave and Butte Valley lavas. Phenocrysts of olivine, up to 1 millimeter in diameter, total 10 percent of the volume. Minute, round granules of augite, less than 0.1 of a millimeter across, constitute approximately 15 percent by bulk. A few phenocrysts of bytownite and microliths of medium to basic labradorite together make up 55 percent of the lava. Between these minerals there is a matrix of black glass heavily charged with dusty opaque ore minerals.

Alder Creek Basalt

From another fissure, near the top of the precipitous north wall of Alder Creek canyon, a younger flow of basalt cascaded 1,700 feet on to the canyon floor, then continued for 2 miles, ending with a steep front as it spread over the Butte Creek basalt. The surface features of this spectacular flow are so well preserved that if the forest cover were removed one might suppose that the lava had been discharged only a few decades ago. Almost certainly it was erupted within the present or the preceding millennium. In contrast with the smooth-crusted Butte Creek basalt, this flow has a blocky to scoriaceous crust, and instead of olivine the most conspicuous phenocrysts are of augite. For most of its length the lava is between 100 and 150 feet in thickness. Where it spread across the canyon floor after tumbling down the wall, it impounded Alder Creek for a time, and it still serves as a partial barrier so that ponds and marshes have developed behind it. Below these, Alder Creek has found a new course along the edge of the flow, but as yet it has scarcely modified the margins.

A sample taken from the snout of the flow is typical of most of the lava. Fresh phenocrysts of olivine and augite, many of which reach a length of 3 millimeters, together make up a quarter by volume. The augite has an optic angle, 2 V, of 50°, and an extinction angle, Z to c, of 42°. The optic angle of the olivine approximates 90°. Laths of basic labradorite, rarely more than 0.1 of a millimeter long, constitute 55 percent of the volume; microlithic hypersthene and augite, in about equal amounts, total 12 percent; euhedral specks of magnetite, interstitial glass, and a little cristobalite make up the remainder.

Eruptions Near Copco Dam

Within the last millennium or two the Klamath River was blocked by flows of basalt to form a lake at least 35 feet deeper than the present Copco Lake at its highest level. The strand lines of this older lake are marked by conspicuous benches of diatomite above the present shores.

Activity began with the formation of three cinder cones on a north-south line. These consist of well-stratified, red, brown, and black cindery lapilli and ash admixed with ropy and spindle-shaped bombs up to a few feet across, as may be seen in the quarry excavated into the side of the middle cone. The cones range from 200 to 300 feet in height; the two oldest, which lie north of the Klamath River, coalesce and have shallow craters; the youngest, on the other side of the river, has a deep and well-preserved crater.

Three flows issued from the foot of the youngest cone, two of them from the north and one from the southeast side, and at least four flows escaped from fissures at the feet of the older cones. The longest flows moved down the gorge of the Klamath River for a distance of almost 2 miles, but most of the others came to a halt within a mile of the source. Since all of them are bare of cinders, it is clear that they were not discharged until explosive activity had come to an end.

For the most part, the individual flows range in thickness between 25 and 60 feet. Their aggregate thickness in the gorge reaches a maximum of approximately 120 feet. Their blocky crusts pass downward into massive, columnar lava. Generally the columns are vertical, but in many places they are strongly curved and locally they diverge downward from vertical axes. In part these curved columns developed where younger flows moved down channels on the surfaces of older flows; in part they resulted from injection of one flow into cracks of another that was already solidified, a phenomenon observed repeatedly among the recent lavas of Paricutin volcano, Mexico.

Since activity ceased, the Klamath River has cut through the basalts to the underlying volcanic rocks of the Western Cascade series, and the snout of the longest flow has been detached from the main body by erosion.

Petrographically the Copco basalts are characterized by abundant clusters of large olivine and plagioclase crystals. Otherwise they are essentially similar to the Pluto's Cave, Butte Creek, and Butte Valley basalts. The olivine phenocrysts reach a length of 2 millimeters, and they total 5 percent of the volume. Optic angles of 84° to 88° (negative) denote compositions between Fo_{72} and Fo_{82}. The porphyritic plagioclase commonly reaches a length of 2 millimeters and varies in composition between An_{79} and An_{93}. They also make up approximately 5 percent by bulk. The fine groundmass consists of the following: round granules of olivine, less than 0.1 of a millimeter, 5 percent; pale-green granules of diopsidic augite, 20 percent; subparallel microliths of An_{73} to An_{78}, mostly 0.1 to 0.3 of a millimeter long, 55 percent; intergranular ore, 10 percent. The lava is therefore classified as a fluidal, intergranular olivine-augite basalt. In some specimens the vesicles are partly coated with opal and/or cristobalite.

Goosenest Volcano

No landmark in the Macdoel quadrangle is more conspicuous than the Goosenest volcano, the top of which rises more than 5,000 feet above the snout of its longest flow. It arrests attention, not only because of commanding height, but also on account of the steepness of its sides in contrast with the gentle slopes of the adjacent shield volcanoes. Even the gentlest, southeast side of the Goosenest slopes at 8°, while the other flanks slope at angles of 14° to 18°, flattening gradually toward the base.

The distribution and attitudes of the older basaltic lavas around the base show that the Goosenest was built on top of a shield volcano that was already much denuded. Essentially it consists of a large lava cone through the top of which protrude the summits of two cinder cones. The larger cinder cone measures between 600 and 700 feet in height and contains a crater about 600 yards across and 200 feet deep. The crater is slightly elongated in an east-west direction and the feeding conduit lies a little west of the center. The smaller cinder cone lies at the southern base of the larger one and, being more denuded, is older. The explosive activity of both cones had almost ended before any of the visible lavas were extruded, although some of the buried flows may have issued as the fragmental ejecta were accumulating.

Most of the lavas spread to the west, and many of them, after tumbling over the cliffed edges of the older basalts, poured down narrow valleys cut in the Western Cascade series. The longest flow followed a valley south of Table Rock, ending more than 6 miles from its source. Other tongues stretched down Wallbridge and Davis Gulches and into the valley of the Little Shasta River. In the opposite direction the lavas moved only for 2 or 3 miles.

The final affusions inundated the western half of the volcano. These issued from fissures at the foot of the summit cinder cone, the concluding gush piling over the source to build a high, east-trending ridge. No one viewing the remarkably fresh appearance of these flows, and noting how little their margins have been affected by erosion, even where bordered by vigorous streams, can doubt that some of them are less than a thousand years old, and that most of them were probably extruded within the last few millennia.

Wells[28] reports that a hot spring formerly existed near the top of the volcano, but no trace of it could be found, nor was any informant questioned who could corroborate its existence.

Lithologically, the Goosenest flows are extremely uniform. All are true block lavas, that is to say they have crusts composed of smooth-faced blocks, up to several yards across, that pass downward through a shattered layer into massive, unbroken lava. In places the surficial blocks are piled in steep mounds, many more than 50 feet high, and in ridges disposed parallel and perpendicular to the directions of flow.

Petrographically, the lavas are hypersthene-rich andesites or perhaps basaltic andesites, markedly vesicular and with a glassy matrix. Phenocrysts of olivine, up to 1 millimeter long, make up only 0.5 to 1 percent of three samples studied microscopically. Porphyritic augite is equally rare. Phenocrysts of hypersthene, on the other hand, constitute between 5 and 8 percent of the bulk. Laths of zoned, medium to basic labradorite, few of which exceed a length of 1 millimeter, total between 40 and 50 percent. The remainder consists of brownish-black glass charged with dusty opaque ore minerals, minute needles of acid plagioclase, and specks of pyroxene.

Last Flows of Shasta and Shastina

The snouts of two Recent flows of andesite erupted from the flanks of Shasta and Shastina lie within the Macdoel quadrangle. The older flow may be seen a short distance to the east of the Dwinnell Reservoir. It is a blocky to scoriaceous, hypersthene-augite andesite with steep margins and a rugged top marked by arcuate ridges and gullies arranged normal to the direction of advance. Along its western side, it overrides the terminal moraines of the Shasta glaciers, but its top is bare of glacial debris and is mantled only by a thin veneer of cinders.

The younger flow, whose high, blocky front is skirted by U. S. Highway 97, is probably the last to be discharged by Shastina. Only a small part of it extends into the Macdoel quadrangle, the entire flow covering approximately 20 square miles. This great flood poured from a series of fissures at elevations of 9,000 to 9,500 feet, not far below the crater rim of Shastina. And they escaped after the formation of two cinder cones, one of which was encircled by the lava while the other deflected its course. Some of the source-fissures are arcuate; others lie radially with respect to the flanks of Shastina. One, illustrated in an earlier report,[29] is a sinuous trench from 30 to 50 feet wide and up to 100 feet deep, with almost vertical walls.

As to the age of these thick, blocky flows, there is evidence that the glaciers of Mount Shasta had dwindled practically to their present extent before the lavas were erupted. Indeed one gush of lava issued from the end moraine of the Whitney glacier, only a short distance below the present front of the ice. If further proof of their youth were needed, it might be found not only in their perfectly preserved, steep fronts, but also in the paucity of vegetation on their tops. The almost complete lack

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[28] Wells, H. L., op. cit.

[29] Williams, Howel, Mount Shasta, California: Zeitschr. für Vulkanologie, vol. 15, pp. 225-253, 1934.

of large trees suggests that some of the lava is no more than a few centuries old. They are mantled only by a light sprinkle of pumice blown from Shasta in 1786.[30]

Petrographically, these last flows of Shastina are olivine-free and olivine-poor, pyroxene andesites, generally devoid of porphyritic feldspar. A sample from the snout of the longest flow, near U. S. Highway 97, is selected for description. In this, few feldspar laths exceed 0.25 millimeter in length, most of them measuring less than 0.1 of a millimeter. They show a strong fluidal alinement. In composition they vary little, all being of medium labradorite. Together they make up 55 percent of the volume. Phenocrysts of diopsidic augite (2V—55°; Z to c—42°), mostly between 0.2 and 0.4 of a millimeter across, but occasionally 1 millimeter long, make up approximately 6 percent. Porphyritic hypersthenes, of about the same size, total only 2 percent. Among the pyroxene microliths, which constitute 5 percent, hypersthene is much more plentiful than augite. The remaining 32 percent of the lava consists of translucent, brown glass ($n = 1.508 \pm .002; = 68$ percent SiO_2) lightly stippled with granular opaque ore minerals.

Summary of the Petrography of the High Cascade Lavas

The volcanic rocks of the Western Cascade series, as noted already, range in composition from olivine basalt to potassic rhyolite. Those of the High Cascades show much less variation, being for the most part olivine basalts, olivine-bearing basaltic andesites, and pyroxene andesites. Some hornblende-bearing andesites are present, and perhaps some of the Haight Mountain lavas are dacites. But rhyolites are absent.

During Pliocene time almost all the lavas were olivine basalts or basaltic andesites. Subsequently, andesites and perhaps dacites were also erupted. In other words, no regular sequence can be detected. With few exceptions, individual volcanoes discharged only one type of lava, but Little Deer Mountain, after erupting olivine basalt throughout most of its activity, discharged flows of pyroxene andesite during the final stages, and Mount Shasta, after growing almost to its full height by effusions of pyroxene andesite, began to erupt dacite and basalt as well.

As in other parts of the High Cascades, the Pliocene and younger lavas of the Macdoel quadrangle belong to the Pacific or calc-alkaline igneous suite.

Moraines and Fluvioglacial Deposits

Moraines. At their maximum extent, which was presumably at the climax of the Tioga stage of the Wisconsin glaciation of the Pleistocene epoch, approximately 25,000 years ago, the glaciers that descended the northwest slopes of Mount Shasta spread into Shasta Valley to an elevation of about 2,800 feet. Their length was then slightly more than 13 miles. Their end moraines are to be seen along the shores of the Dwinnell Reservoir, and their recessional moraines form the cluster of ridges that extend thence southward to Weed.

The limits of the glaciers that formerly covered the northern flank of Shasta are obscured by younger lavas and by fluvioglacial fans, but probably the ice did not extend far beyond U. S. Highway 97, to eleva-

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[30] Williams, Howel, Mount Shasta, a Cascade volcano: Jour. Geology, vol. 40, pp. 417-429, 1932. . . . Mount Shasta, California: Zeitschr. für Vulkanologie, vol. 15, pp. 225-253, 1934.

tions below 4,000 feet. There are no signs of glaciation either on Yellow Butte or on Sheep Rock, and none of the High Cascade cones between Sheep Rock and the Oregon-California aboundary ever supported glaciers. Along the western base of Shasta, south of Weed, the ice descended to elevations of approximately 3,800 feet.

It follows that during the Pleistocene, as today, the longest of the Shasta glaciers were on the northwest flank. But now their length is reduced to a maximum of 2 miles and none descends much below an elevation of 10,000 feet.

An imposing Pleistocene glacier flowed down the canyons of Butte and Alder Creeks for a distance of approximately 12 miles. Although its source lay in cirques on the sides of Haight Mountain at elevations of little more than 7,000 feet, its snout extended down to 4,800 feet, in the vicinity of the Soule Ranch. For most of its course, the glacier was only a mile wide, and it varied in thickness between 400 and 500 feet. It overflowed the western rim of the canyon near Granada Ranch, and it crossed the opposite rim near Mount Shasta Woods. Below these points it left huge lateral moraines in its wake.

Fluvioglacial Deposits. Beyond the ends of the Pleistocene glaciers, wide sheets of outwash were deposited. At the Dwinnell Dam, in a depression between the end moraines, there are well-bedded sands and gravels up to 200 feet in thickness. These were probably laid down in a lake adjoining the front of the ice.

Long ridges of bouldery outwash extend northward from the moraines near Weed through Edgewood into the southwest corner of the Macdoel quadrangle. Where the outwash includes sufficient clay, the surface is characterized by abundant stone circles, as described by Masson in the accompanying report in this bulletin.

Wide fans of sandy, pebbly, and gravelly outwash also spread down the northwest flank of Shasta as the glaciers retreated, and these are still in process of extension, spreading over the low edges of the Pluto's Cave basalt. Periodically, during times of rapid melting, bouldery mudflows still sweep down from the Whitney, Bolam, and Hotlum glaciers.

A hummocky area of fluvioglacial outwash also extends beyond the end moraines of the glacier that formerly occupied Butte Creek canyon. These are coarse, bouldery deposits that grade northward into a gravelly, cinder-covered plain, and their surface is also marked by stone circles similar to those near Edgewood.

STRUCTURE

Folding

An angular discordance separates the Umpqua formation from the Western Cascade series in the southern part of the Medford quadrangle, and in the Yreka and Macdoel quadrangles, indicating upper Eocene earth movements prior to the main eruptions of lava. Locally, the coarse fragmental beds of the Western Cascade series show original dips resulting from accumulation on the flanks of cones, but the finer ejecta and the lavas appear to have been laid down either horizontally or almost so. As noted already, the region occupied by the Western Cascade series must have subsided many thousands of feet as the lavas and ashes accumulated, and presumably this subsidence was greatest in the vicinity of the original cones where accumulation was most rapid. At the same time, the bedrock-region of the Klamath-Siskiyou Mountains, which was undergoing erosion, was probably rising in response to the dictates of isostatic balance. If so, then the Western Cascade series had already acquired regional dips to the east and northeast before the close of the Miocene epoch. The main tilt in those directions and the bodily uplift of the Cascade Range took place, however, at the end of Miocene time.

For the most part, the Umpqua sediments and the Western Cascade beds dip at angles that range from 15° to 20° near the western edge of the quadrangle to approximately 5° along the margin of the High Cascades. Only in one place, near the Hessig Ranch on the Klamath River, is this regional dip interrupted by a flexure. There the volcanic rocks are arched into a gentle anticline pitching to the southeast, precisely where initial dips denote the former presence of a steep volcanic cone. Elsewhere the regional dips are replaced by abnormal attitudes produced by faulting, as noted below.

Faulting

In the Cascade Range of Oregon there is evidence of large-scale faulting at the close of the Miocene epoch, prior to the development of the High Cascade volcanoes. For instance, Thayer [31] has shown that an east-facing fault-scarp at least 2,000 feet high existed in the vicinity of Mount Jefferson before the High Cascade lavas began to accumulate. And Williams [32] has suggested that buried faults with downthrow to the east are also present beneath the High Cascade lavas in the neighborhood of Crater Lake. Admittedly there is no evidence of such faulting of the Western Cascade series in the gorge of the Klamath River, but it may be that north-south faults underlie the High Cascade cones farther south, for along the western border of these cones the Western Cascade series rises to elevations 1,000 to 1,500 feet higher than along the opposite sides. Because the evidence is far from conclusive, these possible faults are not shown in the sections, plate 3.

The oldest faults in the Macdoel quadrangle that can be mapped are those limiting two narrow horsts along the edges of Shasta Valley. One of these horsts lies close to the northern end of the valley, near Snowdon; the other follows the eastern margin of the valley from Yellow Butte northward beyond the Conrad Ranch.

The Snowdon horst is traceable for about 5 miles, although its width nowhere exceeds two-thirds of a mile. Northward it disappears close to the Klamath River; in the oppisite direction it disappears beneath alluvium. Within the horst, the normal regional dips to the northeast give place to northwesterly and west-northwesterly dips, generally at angles of 15° to 20°, or to dips that vary greatly over short distances. The downthrow on the eastern side of the horst diminishes northward from a maximum of approximately 400 feet; the downthrow on the other side cannot be determined with accuracy, but it also diminishes northward from a maximum of perhaps 200 feet. Many minor, normal faults of the same trend cut the coal-bearing Umpqua beds within the horst. It may be significant that numerous dikes of andesite cut the

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[31] Thayer, T. P., Structure of the North Santiam River section of the Cascade Mountain in Oregon: Jour. Geology, vol. 44, pp. 701-716, 1936.

[32] Williams, Howel, The geology of Crater Lake National Park, Oregon: Carnegie Inst. Washington, Pub. 540, 1942.

Umpqua beds inside the horst, and that three bodies of lava, probably the fillings of volcanic necks, are present near the southern end of the horst, just where the displacements reach a maximum.

The second horst, which may be referred to as the Yellow Butte horst, is a much more important structure. It is traceable for approximately 8 miles, widening northward from about half a mile to at least three times that width. The fault bounding the horst on the east, although largely covered by Recent lavas and fanglomerates, is marked in places by springs and artesian wells and by the abrupt termination of Umpqua sediments against the Western Cascade series. Owing to renewal of movement on the fault within very recent times, the trace is further defined by a straight scarp, up to 15 feet high, that cuts the Pluto's Cave basalt and the inliers of Shasta andesite a short distance north of Yellow Butte. Southward the fault passes through the gully on the east side of Yellow Butte and disappears beneath the Shasta lavas close to U. S. Highway 97. Unfortunately the amount of throw on the fault cannot be determined accurately, partly because the relief of the pre-volcanic surface is unknown, partly because rapid lateral variations within the Western Cascade series make correlations hazardous, and partly because there is doubt as to what part of the Umpqua formation is present within the horst. But if the pre-eruption surface was one of low relief, and the Umpqua beds exposed within the horst represent the topmost part of the formation, the downthrow on the fault near the Conrad Ranch approximates 600 feet. Undoubtedly the throw increases southward, since the metamorphic and plutonic bedrocks are revealed inside the horst on Yellow Butte. Thereabouts the throw may be several thousand feet.

The probable position of the fault bordering the Yellow Butte horst on the west is shown on the geologic map, plate 1. Unfortunately the exact position is concealed by the Pluto's Cave lava. As in the case of the eastern fault, the throw diminishes northward, but the precise amount of displacement cannot be told. The trouble is that the Western Cascade lavas in the western half of Shasta Valley show no well-defined dips, and in the other half they are buried by Recent flows. But if the older lavas dip northeastward at angles that diminish in that direction from 15° to 5°, as they do elsewhere, then the throw on the fault in the latitude of Big Springs is not less than 10,000 feet. Opposite Yellow Butte the throw must be much more if the bedrocks there were formerly covered by Cretaceous and Umpqua sediments and by the full thickness of the Western Cascade series.

South of Yellow Butte, the converging faults that border the horst are concealed by andesitic flows from Mount Shasta. They must continue southward for a considerable distance, and it may not be fortuitous that if they maintain the trends they have on either side of Yellow Butte they must come together close to the central vent of Shasta.

From the foregoing it appears that Shasta Valley is a large structural depression, limited on the east by a fault of great displacement. Already, before the first Pliocene eruptions of the High Cascade volcanoes, there was a broad, north-south depression that coincided approximately with the present valley, bordered on the east by a high ridge of Western Cascade rocks. But the drainage of the depression was then quite different from that of today. Proof of this is to be found in the boulders of quartzite beneath the Table Rock basalts, for these were laid down in the bed of a westward-flowing stream, 700 to 800 feet above the present edge of Shasta Valley, despite the fact that the boulders could only have been derived from far to the west, from the Klamath-Siskiyou Mountains. Pebbles and cobbles of bedrock are also present in the upper reaches of Willow Creek valley, and there are broad terraces mantled with bedrock detritus at the northern end of Shasta Valley, east and north of Snowdon. The presumption is that the Shasta River formerly ran close to the edge of the High Cascades and it probably continued northward through what is now the valley of Willow Creek to join the Klamath River about 8 miles above its present confluence. Where the former channel of the river passed by Miller Mountain it was bordered by huge fans of bouldery detritus, up to 300 feet in thickness, that merged upward into pediments, relics of which are still preserved 1,000 feet above the present valley.

Today, Shasta River makes a right-angle bend on leaving the Dwinnell Reservoir, and flows approximately parallel to the margin of the Pluto's Cave basalt for the next 10 miles. There can be little doubt that this course was established only a few thousand years ago, when the original channel was filled by the Pluto's Cave lava.

The ancestral Shasta Valley and the two horsts adjacent to it were probably formed at the close of the Miocene epoch, prior to the growth of the Pliocene shield volcanoes. But Butte Valley and the adjoining fault-scarps were formed much later. Most of these scarps probably date back to late Pleistocene time, but many are so well-preserved as to indicate either renewal of movement or origin in Recent times. The scarps follow two principal directions, one north and the other approximately northwest. As far as can be judged the two sets were formed simultaneously. In several places, as near the Meiss Ranch, the scarps show abrupt changes in trend where the diagonal faults meet the meridional ones.

Butte Valley itself is a complex, down-faulted basin, deepest along its western side. Between Macdoel and Dorris, in sec. 23, T. 47 N., R. 1 W., a well passed through 18 feet of sandy soil, then through 175 feet of clay before entering a bed of cinders. A well at Mount Hebron Station ended in sediments at a depth of 184 feet. But apparently the full thickness of the valley-fill has nowhere been penetrated by borings.

Sam's Neck and Pleasant Valley are two graben projecting beyond the margins of the main depression. The adjacent horsts are tilted westward at angles of 10° or less. At the southern end of Sam's Neck, approximately 2 miles east of Spring School, a sulphur spring occurs at the intersection of two faults.

Orr Lake and the two dry lakes shown on the geologic map, plate 1, occupy graben, and like Meiss Lake the two dry ones lie on the western side of the depressions containing them, suggesting that the down-dropped blocks are tilted in that direction.

Innumerable small displacements cut the Western Cascade series, so that slickensided lava surfaces are extremely abundant, but the trends of these minor fractures and the directions of movement along them are highly variable over short distances. A recent fault cuts the upper flow of basalt forming Table Rock, trending approximately northwestward and with a downthrow to the west of about 15 feet.

GROUND WATER

At the southern end of Shasta Valley, near Pluto's Cave, the water table lies at a depth of approximately 300 feet. Northward it approaches the surface rapidly so that many large springs issue from the basaltic lava, and in Little Shasta Valley ponds and lush meadows occupy the depressions. Several wells in the valley discharge artesian water from shallow depths.

Two artesian wells and several artesian springs, including the copious one that feeds Spring Creek above Conrad Ranch, are situated on the fault limiting the Yellow Butte horst on the east. Along the edges of Shasta Valley numerous small springs issue from layers of tuffaceous clay between the lavas of the Western Cascade series. Springs are also common close to the contact between these lavas and the overlying flows of the High Cascade series.

In the High Cascades themselves springs are found especially under the following conditions: some issue from the flanks of the shield volcanoes, flowing from the porous tops and bottoms of flows or from joints in the lava, as at Spannus and Grouse Springs on the Eagle Rock volcano; others issue from the rims of depressions between adjacent shields, like those that supply Grass Lake, Bull Meadows, and the meadows near Kuck's Cabin; still others are located along faults cutting the lavas, as along the margins of Butte Valley; and finally, some springs gush from tubes in basaltic flows, like those on the Granada Ranch and near Mount Shasta Woods, which pour out of the Butte Creek basalt.

In Butte Valley, ground water is found everywhere close to the surface, so that it is seldom necessary to drill wells below 10 to 20 feet. The water table rises westward, intersecting the surface among the marshes around Meiss Lake.

A description of the Beswick Hot Springs has already been given by Waring.[33] They occur in alluvial flats along the banks of the Klamath River, and formerly they fed hot-mud and clear-water baths at a popular health and fishing resort. The hottest spring then had a temperature of 152° F., and several others were only slightly cooler. Analyses of the water are notable particularly for their high content of sodium chloride and for the presence of borates. Presumably the chlorine comes from deeply buried marine beds of the Chico formation, and probably the borates are derived from the overlying lavas. There is no evidence that the heat is of volcanic origin, for the closest lavas of Recent age lie 7 miles downstream, near the Copco Dam. Nor is there evidence that the springs lie on a major fault, although their position may be related to minor fractures along which there has been little displacement. Indeed such fractures may be partly responsible for the long, straight canyon of Shovel Creek at the mouth of which the Beswick Springs occur. Since the springs issue from the Western Cascade series and this dips eastward throughout a belt that stretches for many miles to the west, it seems likely that the water is forced to the surface from great depth. Certainly that must be so if the chlorine is derived from the Chico beds, since those must lie at least 10,000 feet below.

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[33] Waring, G. A., Springs of California: U. S. Geol. Survey Water-Supply Paper 338, pp. 120-121, 1915.

Waring[34] has also described two clusters of carbonated springs, popularly known as Soda Springs, one near Bogus School and the other near Table Rock. The largest group, the Bogus Springs, includes at least eleven, although at the time of Waring's visit there were only six. Each has built a low mound of calcareous tufa, the biggest measuring 30 feet in height and 30 yards in width. Gas bubbles from all of them. In Waring's report, the temperature range is given as 72° to 76° F. A qualitative analysis made in 1947 by J. D. Howard of Klamath Falls[35] showed the presence of sodium chloride, magnesium and calcium carbonate, sodium phosphate, silica, iron, and traces of lithium and hydrogen sulphide. It is presumed that here also the chlorine originates from Chico sandstones at great depth.

The other group of carbonated springs, near Table Rock, has been discussed by Waring in the report mentioned above. An analysis of water from one of the springs on the north side of Table Rock, in sec. 20, T. 45 N., R. 4 W., formerly bottled as a carbonated mineral water by the Yreka Coca Cola Bottling Works, is cited by O'Brien.[36] It is notable on account of the high content of calcium and sodium bicarbonate and of sodium chloride. On the Martin Ranch, the active "soda spring" issues about 75 yards west of a tufa mound 10 feet high, which was formerly the principal outlet. The presence of this mound and of much tufa cementing the gravels along the banks of the adjacent stream suggest that the waters may formerly have been hotter than at present. Geologic mapping does not indicate the occurrence of any major faults near either the Bogus or Table Rock Springs, but probably they lie on fractures of small displacement.

BESWICK "CRATERS"

In view of the widespread interest that they have aroused, brief mention should be made of the so-called "Beswick Craters" which lie on a spur approximately 350 feet above the Klamath River near its confluence with Shovel Creek. More precisely, they are located a quarter of a mile east of the old Hessig Ranch.

The "craters" consist of a cluster of closely spaced, circular pits from a few feet to 10 feet deep, and from a few feet to about 10 yards in diameter. They are distributed over an area of aproximately an acre, within a hummocky pile of boulders, most of which measure a foot or so across, though a few exceed 3 feet in maximum dimension. These boulders are remnants of one of the intra-canyon flows of High Cascade lava perched on a bench cut in rhyolite belonging to the Western Cascade series.

Most of the "craters" are funnel-shaped, but some of the smaller ones are almost cylindrical. Generally they are to be found on the tops of block-mounds. Occasionally, small pits occur on the rims of larger ones. By some, these features are regarded as products of volcanic explosions, a supposition fostered no doubt by the presence of the Beswick Hot Springs not far away. Indeed, it has been reported that in 1946 a "blow-out" took place at the "craters" and that bushes were uprooted and killed. But close inspection reveals no signs of solfataric or fumarolic activity within the area and no evidences of heat. Explosions powerful

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[34] Op. cit., pp. 217-220.

[35] Oral communication.

[36] O'Brien, J. C., Mines and mineral resources of Siskiyou County, California: California Jour. Mines and Geology, vol. 43, pp. 413-462, 1947.

enough to produce large pits in such coarse, bouldery material would surely have blown finer ejecta to great distances, but there is no hint of such debris. The conclusion is inescapable: the "craters" are not volcanic. Probably one is confronted here with the dismembered relics of a basaltic flow, with a field of residual blocks the hummocky surface of which results either from unequal erosion of the underlying rhyolite or from deposition on an uneven surface. Currents of cold air issue from the bottoms of some of the "craters," suggesting the presence of subterranean channels. Doubtless the shapes of some of the "craters" have been modified by "pot hunters" and perhaps some of the pits were formerly utilized by Indians, many of whom used to camp along the Klamath River and Shovel Creek.

ECONOMIC GEOLOGY

Coal

Thin beds of lignite and sub-bituminous coal have been found at several localities along the edge of Shasta Valley within the Umpqua formation. The principal workings are at the Ager coal mine on the Hagedorn Ranch, approximately 5 miles south of Ager, adjoining the Ager-Montague road on the west. According to Averill,[37] the main seam reaches a thickness of 6 feet, but the best part varies between 14 inches and 4 feet, averaging 2 feet. The seam pinches and swells rapidly and it includes and is underlain by thin layers of carbonaceous shale. The beds dip to the northeast at 18° for the most part, but at higher angles where they are cut by small, normal faults. An incline has been driven down the dip for 700 feet, and from this three drifts run north for a maximum distance of 500 feet and south for a maximum distance of 400 feet. A production of 100 tons, valued at $500, was reported in 1914 by the Yreka Development Company, then lessee.[38]

Averill states that numerous prospect holes have been drilled near this mine on the Herr, Cooley, and Denny Ranches. On the Cooley Ranch, a hole was bored to a depth of 130 feet by C. B. Kay, on the strike of the Ager seam, passing through 11 feet of coal at a depth of 118 feet. Another hole, 106 feet deep, is said to have struck 20 inches of coal at a depth of 95 feet. Averill also records the occurrence of small streaks and spots of soft coal and a seam up to 2 inches thick near Hornbrook. There can be little doubt that these are also in the Umpqua formation, and that they lie on about the same horizon as the more extensive coals found near Ashland and Talent in Oregon.[39]

Thin beds of coal are also present near the base of the Umpqua formation in the hills east of Yreka. These do not appear to have been exploited commercially.

A bed of lignite and lignitic shale occurs between the volcanic rocks of the Western Cascade series on Glenn Williams' ranch in sec. T. 44 N., R. 4 W. Its extent and thickness are not known. Other coal deposits, on approximately the same horizon, are reported to be present on the northern flank of Bogus Mountain, but these were not located.

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[37] Averill, C. V., Mines and mineral resources of Siskiyou County: California Div. Mines Rept. 31, pp. 255-338, 1935.

[38] O'Brien, J. C., op. cit., p. 423.

[39] Diller, J. S., The Rogue River Valley coal field, Oregon: U. S. Geol. Survey Bull. 341, pp. 401-405, 1907.

Copper and Molybdenum

The Yellow Butte mine, comprising approximately 318 acres of patented land in the W ½ sec. 25, T. 43 N., R. 4 W., lies on the northeast slope of Yellow Butte. It is assessed to the Lone Hill Mining Company.[40] The workings occur in a body of coarse-grained hornblende-biotite quartz monzonite close to its contact with Paleozoic (?) quartzites and siliceous schists. Averill [41] stated that an inclined shaft, about 300 feet deep, had recently been retimbered for 35 or 40 feet, but in 1948 the shaft was caved 10 feet from the collar. The plutonic rock here is cut by shear planes and stringers of quartz that strike in general N. 25° E. and dip 70° NW. No ore was seen in place, but specimens of vein quartz on the adjacent dump carry pyrite, molybdenite, chalcopyrite, and chrysocolla. Production has been small but exact figures are not available.

Several prospect pits have been driven into the quartzites close to the monzonite, and others may be seen in the metamorphic rocks on the western side of Yellow Butte, but all appear to be barren of ore.

In view of the fact that Yellow Butte is a narrow horst bounded by north-trending faults of great throw, the limits of practicable mining are much restricted.

Building Stone and Crushed Rock

Sandstone. The massive Chico sandstones forming the outlier approximately 2 miles northeast of Yreka, have been quarried for building stone.[42] Similar rocks have also been worked on a small scale in the vicinity of Camp Lowe and Hornbrook.

Lava. An immense supply of lava is available both for building stone and road metal. To date only the lavas of the Western Cascade series in Shasta Valley have been utilized, although many of those forming the High Cascade volcanoes are equally satisfactory.

The Western Cascade andesites are particularly useful for crushed rock where they are cut by closely spaced, platy joints and break with a hackly fracture. Much andesite of this kind is to be found among the hillocks in the western half of Shasta Valley, but only at one locality, in sec. 25, T. 45 N., R. 6 W., has it been quarried on a large scale. The material here proved satisfactory for surfacing the Siskiyou County Airport. Blocky andesite has been quarried for road metal in sec. 36, T. 45 N., R. 5 W., and in sec. 29, T. 44 N., R. 5 W., but no use seems to have been made of the massively jointed, dense andesite widespread along the southwest margin of Shasta Valley.

Rhyolitic lava has also been quarried for the surfacing of roads. The two principal localities are as follows: on Drop-off, in sec. 16, T. 44 N., R. 5 W., where the long slides of talus below the summit-cliffs have been worked on a small scale; and on Cemetery Knoll, near Little Shasta, in sec. 36, T. 45 N., R. 5 W.

The Pluto's Cave basaltic lava, owing to the ease with which its jointed crust breaks into cuboidal blocks, has been widely utilized by ranchers for construction of stone fences.

Rhyolite Tuff. Because most of the rhyolite tuffs of the region are friable and pulverize easily into fine dust, little use has been made of them.

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[40] O'Brien, J. C., op. cit., p. 428.
[41] Op. cit., 1935, pp. 273-274.
[42] Averill, C. V., op. cit., 1935, p. 337.

But locally, as in sec. 7, T. 47 N., R. 4 W., close to the Ager-Beswick road, the firmer, welded types have been excavated for road metal.

Other Volcanic Rocks. A large quarry in sec. 7, T. 45 N., R. 5 W., was opened up recently for materials to surface the Siskiyou County Airport. It occurs in mudflow (lahar) deposits of the Western Cascades series that consist of large boulders of andesite, rhyolite, and quartzite set in a matrix of red, tuffaceous clay. Owing to the nature of the fine constituents, the material proved to be unsatisfactory.

Basaltic cinders have been utilized extensively in the surfacing of highways and logging roads, and by the Southern Pacific Railroad as ballast. The material is unusually easy to quarry, and, being a mixture of small, dense lava fragments with porous, cindery debris, it is ideally suited for the purposes mentioned. The chief quarries are as follows: in the southern of the two cinder cones near Copco Dam; the Soule Ranch and Kegg cones; and on the south slopes of Little Deer Mountain (see geologic map, plate 1).

Sand and Gravel. Fluvioglacial sediments consisting mostly of rolled fragments of andesitic lava and pumice have been worked on a small scale for use on roads, as for instance near U. S. Highway 97, southwest of Haystack Butte. Similar deposits extend westward in a large fan as far as the Dwinnell Dam.

Diatomite

Deposits of diatomite extend around the shores of Copco Lake to an elevation of approximately 35 feet above the present water surface. They are most extensive on the benches fringing the northern shore. No effort seems to have been made to utilize them, although they contain only a small amount of clastic detritus.

Ornamental and Gem Stones

The fossiliferous Chico sandstones on the Hagedorn and Richardson Ranches in the NE¼ sec. 26, T. 46 N., R. 6 W., split readily along the bedding planes, can be cut easily in other directions, and take a beautiful polish. Attractive articles of small size have been made from them by C. B. Kay of Montague.

Opal and agate are plentiful among the lavas of the Western Cascade series, particularly in those about half way to two-thirds of the way up in the series. They are abundant, for example, on Agate Flat, close to the Oregon-California boundary; also on the slopes of Bogus Mountain and among the hills to the south that lie near the edge of the High Cascades. Only rarely do the minerals occur in large amygdules; for the most part they form narrow veins cutting the lavas or are found as loose fragments in the soil. In general they are milky white and show concentric banding, but "moss agates," carnelian, and greenish varieties of chalcedony are also common. Among the tuffs and tuffaceous sediments interbedded with the lavas, there is much petrified wood, notable occurrences being on Agate Flat and in secs. 15 and 16, T. 46 N., R. 5 W.

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CIRCULAR SOIL STRUCTURES IN NORTHEASTERN CALIFORNIA

By Peter H. Masson

OUTLINE OF REPORT

ILLUSTRATIONS

ABSTRACT

Many low mounds 2 to 3 feet high and up to 85 feet in diameter, each of which is surrounded by a ring of loose stones, have been found in several parts of northeastern California. Although it was first thought that early Indians were responsible for the structures, no evidence in support of this view was produced, and certain observed features were deemed incompatible with such a mode of origin. Similarities between these rings and structures in other parts of the world which have been attributed to freezing and thawing of the soil suggest that the California rings have also resulted from frost action. The mechanisms involved, as described by other writers, are briefly reviewed herein and applied to these structures. It is concluded that doming results from the concentration of clay in certain centers and that formation of rings follows as surface stones are displaced from the domed areas. These processes are controlled by freezing and thawing of water-saturated soil. In support of this theory, measurement of the clay content of various soil samples indicated that concentration of clay had actually taken place.

INTRODUCTION

In the Fall of 1946 attention was called to several areas containing low mounds encircled by rings of loose stones in central Siskiyou County, California. It was thought that the rings were the work of early Indians and popular interest was aroused. However, no positive evidence in support of such a view could be found and, to the writer's knowledge, a satisfactory explanation for the origin of these peculiar structures was not advanced. Mr. Franklin Fenenga of the California Archaeological Survey, who examined the rings when they were first noticed, stated that the mounds were undoubtedly not the work of human beings. He stated further that he could see no human function for which they could have been built and that there would unquestionably be some evidence of human association if the mounds were artificial.

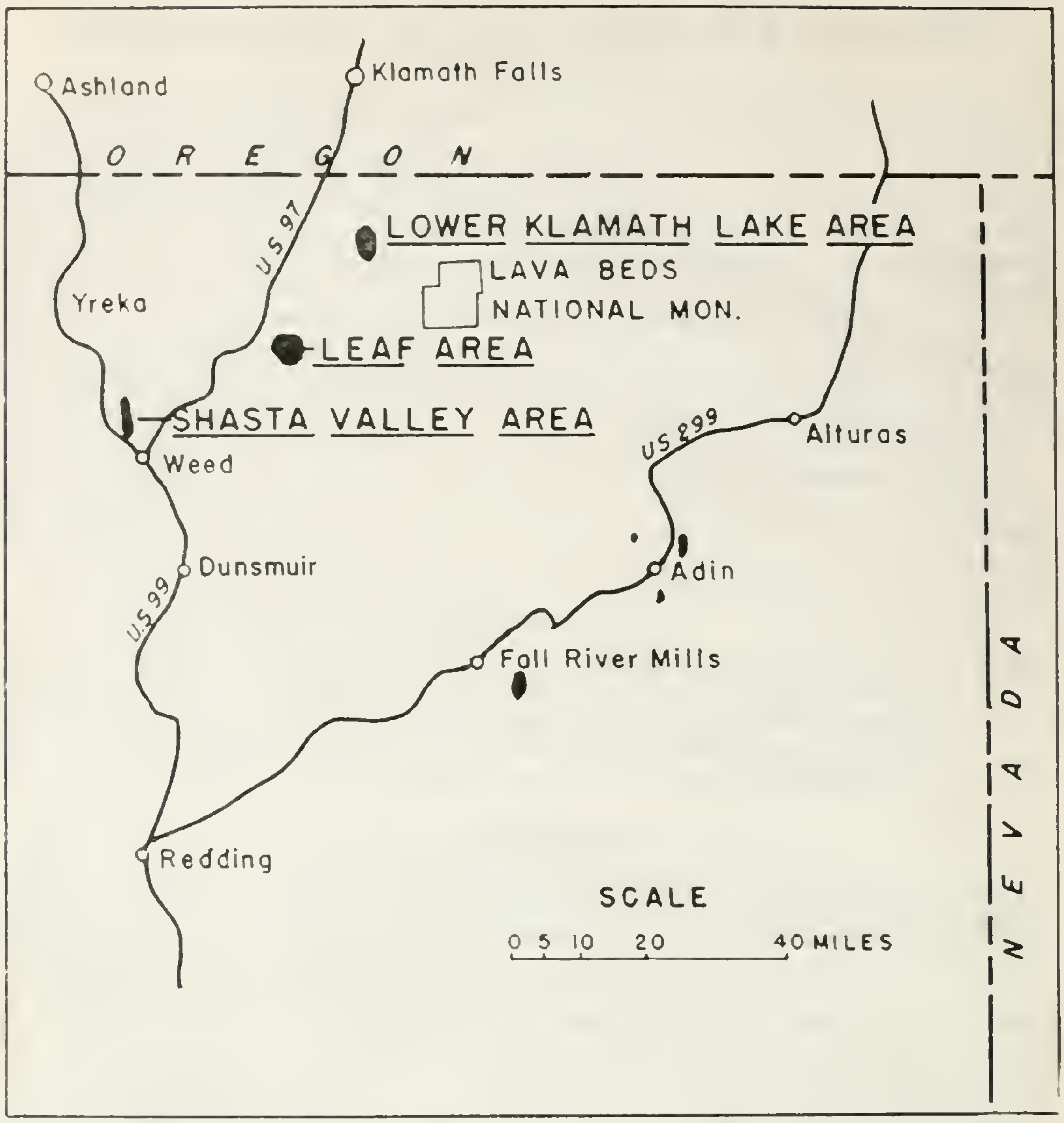

Fig. 1. Index map showing location of circular soil structures.

One such area of rings is at the southwest end of Butte Valley, near Leaf. The best rings are found in sec. 30, T. 44 N., R. 1 W., M.D., and sec. 24, T. 44 N., R. 2 W., M.D. A second area, approximately 4 miles long and averaging 1 mile in width, lies at the south end of Shasta Valley in secs. 8, 17, 20, and 29, T. 42 N., R. 5 W., M.D. Since the conclusion of the present inquiry, the interest and efforts of Mr. Herrick C. Brown, of Oakland, have resulted in the discovery of mounds and stone circles in other areas widely distributed in northeastern California. Soil structures were found around the south end of Lower Klamath Lake in eastern Siskiyou County, in the vicinity of Fall River Mills in eastern Shasta County, and over a large area in southwestern Modoc and northeastern Lassen Counties in the vicinity of Adin.

DESCRIPTION OF THE SISKIYOU STRUCTURES

Leaf Area

The soil structures are of two types. Those near Leaf consist of low mounds rising 1 foot to 2 feet above the surrounding level surface. They

FIG. 2. Photo showing circular soil structure. Mount Shasta in background. *Published by courtesy of Oakland Tribune.*

are encircled by shallow trenches 6 to 8 inches deep and 1½ to 3 feet wide filled with pebbles and cobbles ranging up to 12 or 14 inches on the longest diameter. There are some boulders 2 to 3 feet in diameter. Within these rings the surface of the mounds is stone-free soil, while all of the surrounding area is evenly paved with stones so that little underlying soil is visible. The coarse debris is made up of a mixture of fine- to medium-grained andesitic and dacitic lavas. Most of the fragments are well rounded but they grade to sharply angular forms. All types are indiscriminately mixed both in the rings and in the surrounding pavement. Examined on the edges and in road cuts, the low terrace-like plateau which bears the rings was found to consist entirely of an unstratified mass of this mixed debris in an unconsolidated matrix of sand and silt, representing fluvioglacial outwash adjoining the end moraines of the glaciers that formerly flowed down Butte Creek Canyon to the vicinity of Soule Ranch. At Camp Leaf this formation is 20 to 25 feet thick.

Most of the rings are perfectly circular or very nearly so, the only variation occurring where adjacent rings coalesce or where a ring is on the sloping edge of the terrace. In the latter instance the downhill side of the ring breaks outward forming a U-shaped structure open on the lower side. Several rings may be arranged in straight lines. Usually closely adjacent rings in these lines coalesce, resulting in a low, straight ridge bounded by scalloped patterns in the stone-filled trenches.

The maximum diameter for single circles is about 85 feet.

Shasta Valley Area

Some of the Shasta Valley mounds are of the type described above, but in most places the definite stone-filled rings have not formed. Here, the mounds are closer together and are simply raised, circular, bare spots in the stone pavement. Linear arrangements are difficult to detect on the ground at this locality but they are apparent from the air. The circles occur in coarse, unstratified fluvioglacial deposits laid down just beyond the terminal moraines of the Pleistocene glaciers that descended from the flanks of Mount Shasta as far as the Dwinnell Dam. The constituent materials are entirely composed of Shasta andesite, angular and subangular pebbles and boulders lying in a matrix of sand and clay. The deposits have been dissected to a depth of about 50 feet by Parks Creek on the west and by Shasta River on the east.

ARE THE CIRCLES MAN-MADE?

Reference has already been made to the view that the rings represent the work of an early Indian culture, a concept strengthened by the geometrical perfection of the rings as well as by the sharpness of their delineation and the presence, in a few cases, of evenly spaced scallops and cog-like protuberances around the peripheries. No artifacts have been found either in the mounds or unquestionably associated with them. In addition, areial photographs show that the rings are exceedingly numerous, not only at the localities described, but throughout northeastern California. The labor involved in such wholesale construction requires a temperament which does not coincide with that generally ascribed to the aborigines of the northwestern United States. In the Leaf area, there is a linear arrangement of the rings, which trends N. 45° W. and holds this bearing on each side of Butte Creek. The rings in this area are on a low, flat-topped plateau that has been cut through by the broad, shallow valley of Butte Creek. Apparently the controlling feature for this northwesterly trend was originally continuous prior to the stream incisions and the depth and breadth of the Butte Creek bed indicates that a long period of time has elapsed since the origin of this controlling feature. If the rings had attained their present form prior to the cutting of Butte Creek Valley they would certainly be at least partly obliterated by infilling, and buried by washed and wind-borne soil, instead of having the clear, sharp outlines to be seen today. What is required to explain them, then, is a process that could be controlled by some early pre-valley feature, yet be operative down to recent or even present times. The human agent most certainly does not meet these requirements.

THE PROBABLE ORIGIN

In Alaska, Canada,[1] the northeastern United States [2] and Europe, similar, but not identical, structures have been attributed to the action of frost and ground ice. In those regions, there are polygonal networks of loose stones instead of rings, and the areas within the polygons are usually flat instead of being domical. There is, however, general agreement concerning the processes involved in the formation of the polygon nets and it seems likely that the same processes are responsible for the structures in Siskiyou County. These processes are summarized by Antevs as follows: (1) the concentration of clay into local centers; (2) the upfreezing of stones to the surface; (3) radial or centrifugal movement of stones in the clay centers during freezing and thawing.

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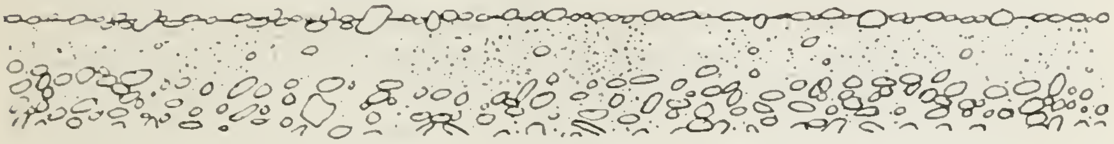
[1] Sharp, Robert P., Soil structures in the St. Elias Range, Yukon Territory: Jour. Geomorphology, vol. 5, no. 1, pp. 274-301, 1942.

[2] Antevs, Ernst, Alpine zone of the Mt. Washington Range, 118 pp., Auburn, Maine, Merrill & Weber Co., 1932.

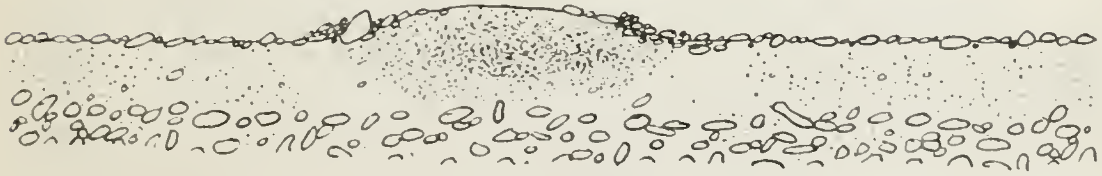
The Concentration of Clay

Due to initial heterogeneity in the distribution of clay in the soil, certain areas near the surface hold more water than others. Clay-rich areas, since they can hold more water, will upon saturation and freezing expand in relation to the surrounding soil. Conrad [3] states that a saturated cube consisting of 70 percent soil and 30 percent water expands on

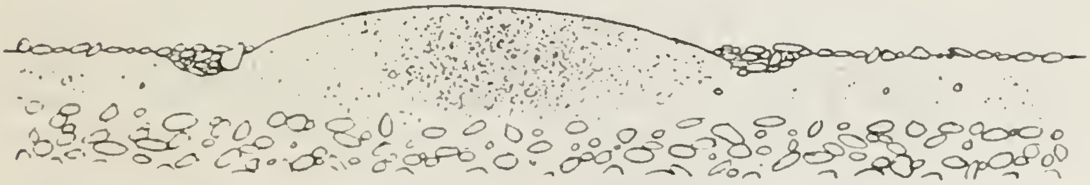
Initial distribution of clay and stones.



Upfreezing has produced stone pavement and clay has begun to concentrate in center.



Doming has begun and pavement in center of dome has started to work outward.



Mature dome structure with stone-filled ring trenches and stone-free center. Not to scale.

FIG. 3. Diagrams showing origin of circular soil structures.

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[3] Conrad, V., Polygon nets and their physical development: Am. Jour. Sci., vol. 244, no. 4, pp. 277-296, 1946.

its edge by a factor of 0.01 upon freezing, and that the increase in radius of a saturated spot will be 0.01 times the radius of the spot. When adjacent clay patches touch during this expansion and then contract as a result of mutual adhesion of the clay-sized particles during thawing and drying, part of the smaller patch may be drawn into the larger one. By repeated expansion and contraction, a clay patch may thus grow in size at the expense of the surrounding soil until a large, slightly domed concentration of clay-rich soil is formed.

Upfreezing of Buried Stones

This process depends upon the principle that freezing begins at the surface, the frozen zone thickening downward; thawing also begins at the surface, the thawed zone thickening downward. When freezing begins, the top of a large stone is firmly held by the surface ice sheet. Freezing below this level forces both the sheet and stone upward by expansion of newly forming ice. Since the bottom of the stone is held only by unfrozen soil, it is easily lifted with the surface sheet, the effect being more pronounced the larger the stone fragment. It is also probable that the void below the lifted stone is filled by inflow of saturated soil so that the sinking of the stone to its original level during thawing is prevented. During thawing the top soil layers contract and settle down relative to the stone which is still held fast by ice at its base. When this ice melts the stone settles but by an amount smaller than the initial uplift. In this manner buried stones are eventually deposited on the surface. This process undoubtedly plays a large part in the formation of the loose stone pavements commonly observed in alpine regions.

Radial Movement

The radial displacement of stones to the rings and polygons probably results from a combination of several mechanisms. As soon as the doming of the clay mass has been accomplished, the radial direction becomes also a downhill direction. Two processes may then become active. One is the well-known frost-heave action by which stones are lifted perpendicular to the sloping surface during freezing but drop vertically during thawing so that there is a downslope movement by repeated short steps. The other process is simple sliding caused by almost frictionless shear planes developed between ice layers during thawing.

Conrad states that the radial expansion of the freezing clay patches is the most important factor in the outward movement of stones on the surface. Expansion carries the stone outward but thawing does not cause a return to the initial position because the soft, saturated soil has not the consistence to carry large stones and because this movement would be uphill. Therefore, after each thaw the clay particles are drawn back by adhesion while the larger fragments are left in displaced positions because they are not affected by adhesive forces.

In this manner the growing clay patches simultaneously purge themselves of the larger sizes and add to themselves by the force of adhesion between colloid and clay size.

Experimental Evidence

In order to test the applicability of these three processes in the Siskiyou County mounds a closer examination was made of several of the more perfectly formed rings at Leaf.

A trench was dug from several feet outside a ring to a point several feet inside the enclosed mound. The observed cross-section is shown in figure 3. Outside the ring the surface pavement is superficial; below it is a soil layer 8 to 10 inches deep which is nearly free from stones. Below this depth, stones are again abundant and keyed in a soil matrix so that digging is very difficult. The ring itself was 3 feet wide and 6 to 9 inches deep in the center, and stones in it were clean and free from soil; in other words, the trench had not been filled at the bottom to any great extent. The surface pavement stops at the ring but the lower stone surface continues uninterruptedly beneath the mound.

One important feature of this cross-section is the presence of the stone-free stratum immediately below the surface. Here is good evidence that the upfreezing process has been operative. Apparently the mechanism is effective only to a depth of 10 or 12 inches; that is, to the depth of the soil layer. Since the proportion of large sizes to the soil matrix is high in this formation, it is possible that below a poorly consolidated top layer a foot or so thick the stones are too well keyed to be raised by the freezing process.

A series of experiments by Taber [4] suggests another possible explanation. He found that frost heaving in almost pure clays was due to the formation of pure ice layers between bands of clay, the vertical thrusting being due to the growth of these layers rather than to the volume increase of frozen, saturated soil. Water to form the layers was drawn from below by surface tension in the minute intergranular openings of the clay. Therefore, the depth to which heaving occurred was dependent upon the amount of water supplied from below. This amount was dependent upon the depth from which water could be made to rise, which was in turn dependent upon the grain size and consequent capillarity of the sediment. The extent to which this phenomenon occurs, therefore, is controlled by the clay content of the soil, there being no effect in sandy, clay-free soil and perfect layering in pure clays. This mechanism causes much greater vertical movement than simple volume expansion and offers a better explanation for upfreezing. In addition, it provides a possible reason for the thinness of the superficial stone-free soil band, since the size-composition of the soil limits the depth to which heaving can operate.

Two readily observable features suggest that concentration of clay into mounds has occurred. In many places the vegetation within the rings is notably different from that covering most of the terrace surface. Outside the rings, the cover is sparse grass and scattered low bushes, but on the mounds the grass and brush are thicker and grow to much larger size. Occasional small juniper trees are also limited to the mounds and several of the straight ridges have lines of trees down their centers. This difference is probably due both to the greater retention of water by the clay and the greater rapidity of the chemical destruction of these finely divided minerals. This feature is not apparent in the Shasta Valley mounds because the area is used for grazing.

A second noteworthy feature is the limitation of most of the single rings to a maximum diameter of about 85 feet. This condition suggests that some control prevents further growth of the mounds and rings. Probably this control is the proportion of clay in the soil. It seems rea-

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[4] Taber, Stephen, The mechanics of frost heaving: Jour. Geology, vol. 38, pp. 303-317, 1930.

FIG. 4. Detail of one of the bordering rings. The mounded side is on the right.

sonable to assume that when a mound has grown to some maximum size by concentration of clay from the surrounding soil, a stage is reached in which the mound is encircled by a band of clay-free soil too wide to allow capture of additional clay from the outside.

In an effort to test this hypothesis a series of soil samples was taken from each of four mounds, three from the Butte Creek area and one from Shasta Valley. These samples were screened down to about minus 0.03 inches and small grab-samples were taken by equal volume. These samples were placed in test tubes and water was added to the same height in each. After thorough agitation, the suspended samples were allowed to stand undisturbed.

According to Stoke's Law, the velocity with which a particle falls through a liquid is largely dependent upon the size of the particle, the smallest particles falling most slowly. Therefore, after a given time all particles remaining in suspension above a given depth will be less than a certain size which may be computed by Stoke's Law.

The samples from each series were run together so that they could be observed side by side during the settling process. In general, suspensions of those samples from the immediate vicinity of the rings were the least dense after settling from 2 to 20 hours. Samples from within the mounds were the most dense, with the exception of No. 6, and those from presumably unaffected soil varied between these extremes. These observations seem to prove that concentration of clay in the mounds takes place at the expense of the surrounding soil.

For a more complete comparison of the samples, the transmission of light by the suspensions was measured. This method was necessary because equipment for the usual type of wet mechanical soil analysis was not available. A strong beam of light was passed through the suspensions at a depth of 5 centimeters and at timed intervals the intensity of this beam was measured with a photoelectric light-meter. Since the intensity of passed light varies inversely with the amount of material in suspension, these readings were inverted by dividing them into the maximum intensity reading for clear water. The logarithms of the values thus obtained were plotted against grain size. Grain size was computed with a Stoke's Law nomograph. Since the fines were mechanically divided by fluvioglacial action, they consist predominantly of the original minerals of the andesitic rocks from which they were derived. Consequently, the specific gravity used in determining the grain size was that of an ideal andesite, about 2.65.

Inspection of the resulting curves revealed the increasing concentration of clay inward from the rings. Smaller grain sizes are prominently deficient at the outer edge of each ring. This relation is shown in figure 5, in which the measured amount of the 0.002 mm size in the samples is plotted against cross-sections showing the points at which the samples were taken.

From these observations it is concluded that the formation of the stone rings was accomplished in the following manner: first, upfreezing of stones in the top 12 inches of the unconsolidated detrital material with the formation of a loose surface pavement; second, concurrent gathering of clay in the soil into centers of concentration; third, the completion of this process with doming accompanied by the beginning of radial displacement of the surface pavement; fourth, concentration of the displaced surface stones into a ring at the outermost limit of the clay concentration; fifth, cessation of growth of the mature structure upon development of a clay-free ring at the outer edge of the stone ring; sixth, entrenching of the stone ring by the upfreezing process; and seventh, maintenance of soil-free trenches by upfreezing and removal of inwashed clay by the annual freezings and thawings.

Regarding the last two steps, it may be pointed out that the upfreezing mechanism brings about a relative movement between stones and soil. Where stones are piled up or concentrated from above as in the rings, the lower stones tend to sink into loose, saturated soil under the weight of overlying stones. The upfreezing mechanism tends to return these stones to positions on top of the soil by raising the stones and pushing the unfrozen soil downward. The sinking and freezing processes both displace soil from the ring area and it appears that competition between the two over a period of time results in the development of the soil-free trenches in which the stone rings are found. The void resulting from removal of the clay fraction undoubtedly aids the process and may even be the most important factor. Clay washed into the bottom of the trench from the mound would be drawn back by the same process that brought about the original concentration.

The intergranular adhesion of the clay particles through the medium of absorbed water may be likened to the intermolecular attraction in liquids in which the resultant surface tension causes spherical bounding surfaces wherever possible. Unbalanced adhesive attraction between particles at the outer edge of the clay mass would result in a surface tension around the mass and it is logical that, weak as this effect may be, the final result of numerous adjustments during freezing and thawing would be the present perfectly circular outline of most of the mounds.

In the Shasta Valley area the stone pavement is much thicker and coarser, and the mounds are closer together, than in the Leaf area. Apparently these two conditions have combined to obscure the formation of

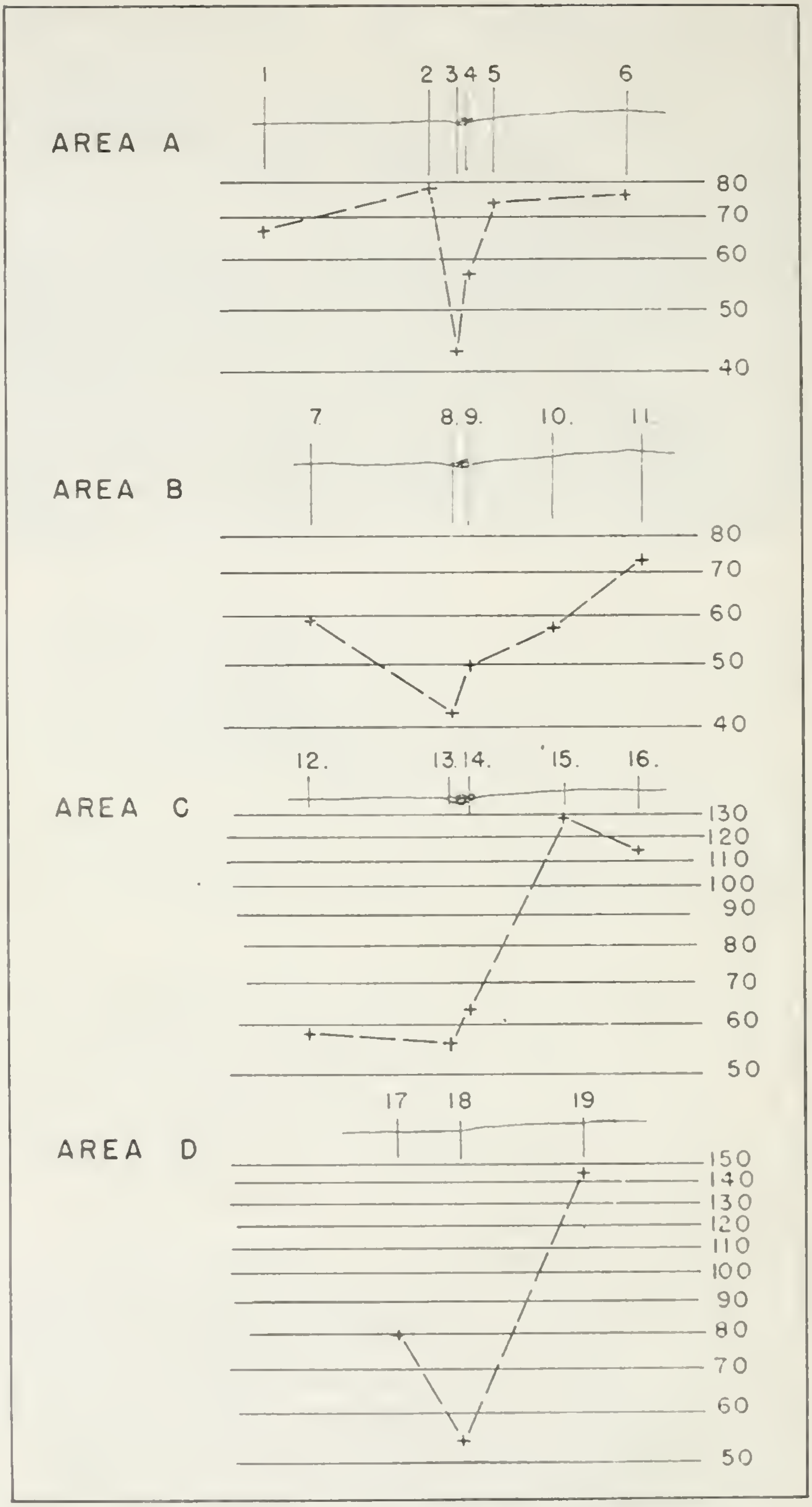

FIG. 5. Distribution of clay (.002 millimeter grain size) in cross section. Numbers at the right edge are relative optical density of the suspensions.

definite rings. The stones expelled from the closely spaced mounds have collected in the intervening low areas as a more or less even pavement, rather than in rings surrounding isolated mounds.

A possible control for the linear arrangement of some of the rings lies in the origin of the detrital formations in which they are found. In both areas, these formations are of fluvioglacial origin. As previously mentioned, they consist of unstratified debris, the Shasta Valley deposits being related to the former glaciers of Mount Shasta, while those of Leaf are related to the ice that formerly flowed down Butte Creek Canyon from cirques near the summit of Haight Mountain volcano. Probably the lines of mounds mark the courses of streams that issued from the snouts of the glaciers. The latest streams would carry large amounts of rock flour which, although very fine, would be deposited along the stream channels upon the disappearance of the water into the porous deposits below. In this manner the fine constituents would be concentrated along the channels to cause the linear groups of rings.

The formation of stone-fringed ridges results from the coalescence of aligned, closely spaced circles. The portion of the stone rings between the joined mounds moves down each side of the resultant divide to produce a continuous ridge bordered on each side by looping stone-paths.

It is not to be assumed from the foregoing that soil of fluvioglacial origin is essential to the development of mound and ring structures. The Lower Klamath Lake, Fall River Mills, and Adin areas are in lava fields in which no glacial deposits are known to exist. At the present time rigorous winters with frequent periods of low temperature are common to all of the areas mentioned. This condition must be a major factor causing the formation of mounds.

SUMMARY

To summarize the formation of these particular structures the following events may be visualized. The initial stage was the deposition of fluvioglacial outwash. As the glaciers receded, fine detritus and rock flour were spread over the surface in increasing amount by the braiding of the outwash channels. After a time the climate became warmer so that long, uninterrupted periods during which the ground remained frozen gave way to shallow but frequent freezings and thawings, and the soil structures began to develop. New drainage patterns replaced the ephemeral glacial streams so that valleys were cut through the earlier deposits. Most of the soil structures probably reached a mature form at an early date; but continuing rigorous winters have resulted in frequent expansions and contractions of the mounds, so that the perfect forms and sharp outlines seen in most of the structures were developed, and maintained down to the present time.

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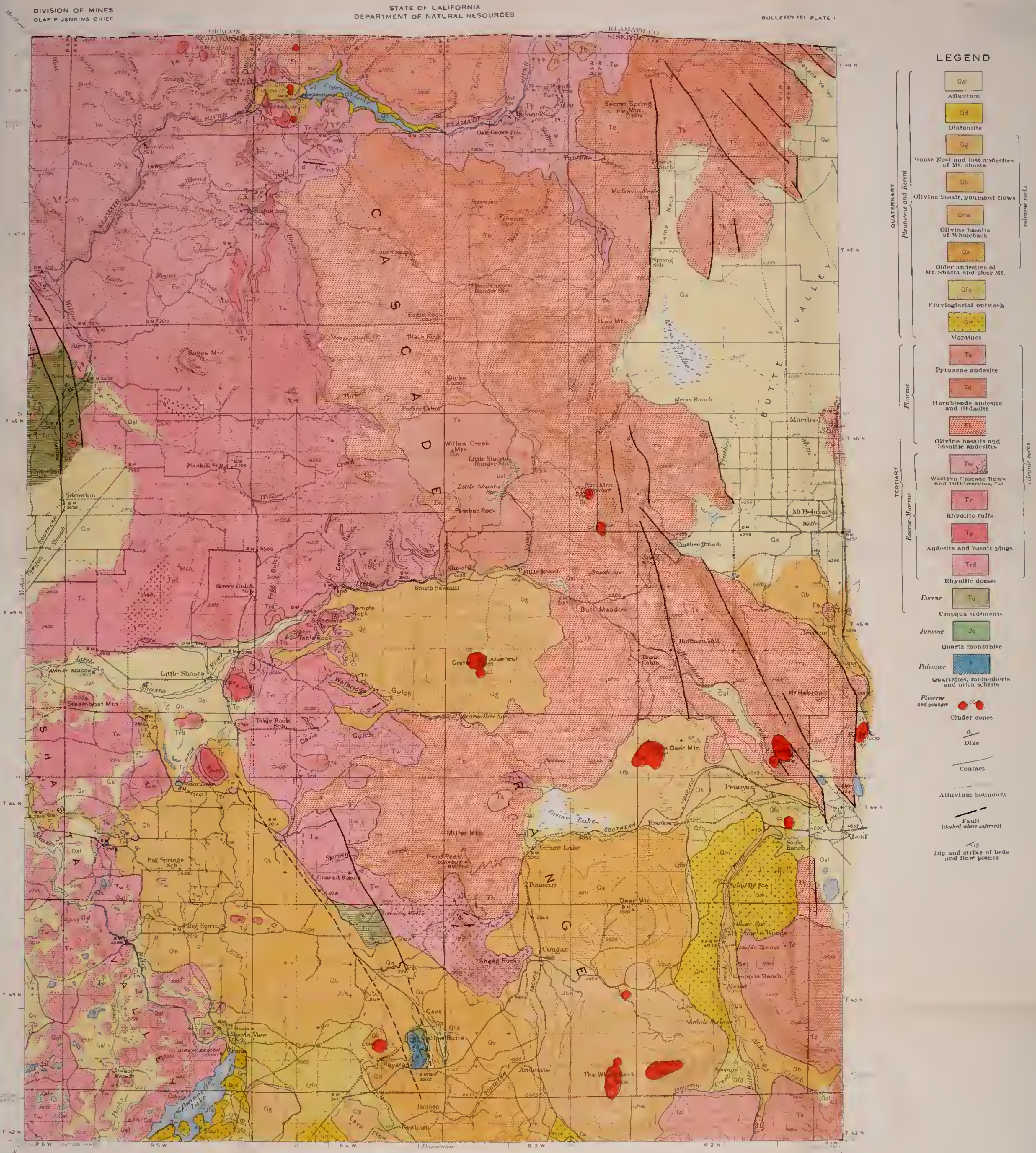
OLAF P JENKINS CHIEF

STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 151 PLATE 1



Topography by C A Ecklund, E P Davis,
T H Moncure, C A Stonesifer, R A Kiger
L O Newsome, R R Monbeck, and
U S Forest Service
Surveyed in 1921-1922 and 1932-1933

GEOLOGIC MAP OF THE MACDOEL QUADRANGLE, CALIFORNIA

By Howel Williams

Geology surveyed in 1935-36 and 1948

Scale $\frac{1}{125000}$

1 ½ 0 1 2 3 4 5 Miles

1 ½ 0 1 2 3 4 5 Kilometers

Contour interval 100 feet
Datum is mean sea level

DIVISION OF MINES
OLAF P JENKINS CHIEF

STATE OF CALIFORNIA
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Surveyed in 1921 1922 and 1932 193-

ECONOMIC MAP OF THE MACDOEL QUADRANGLE, CALIFORNIA

By Howel Williams

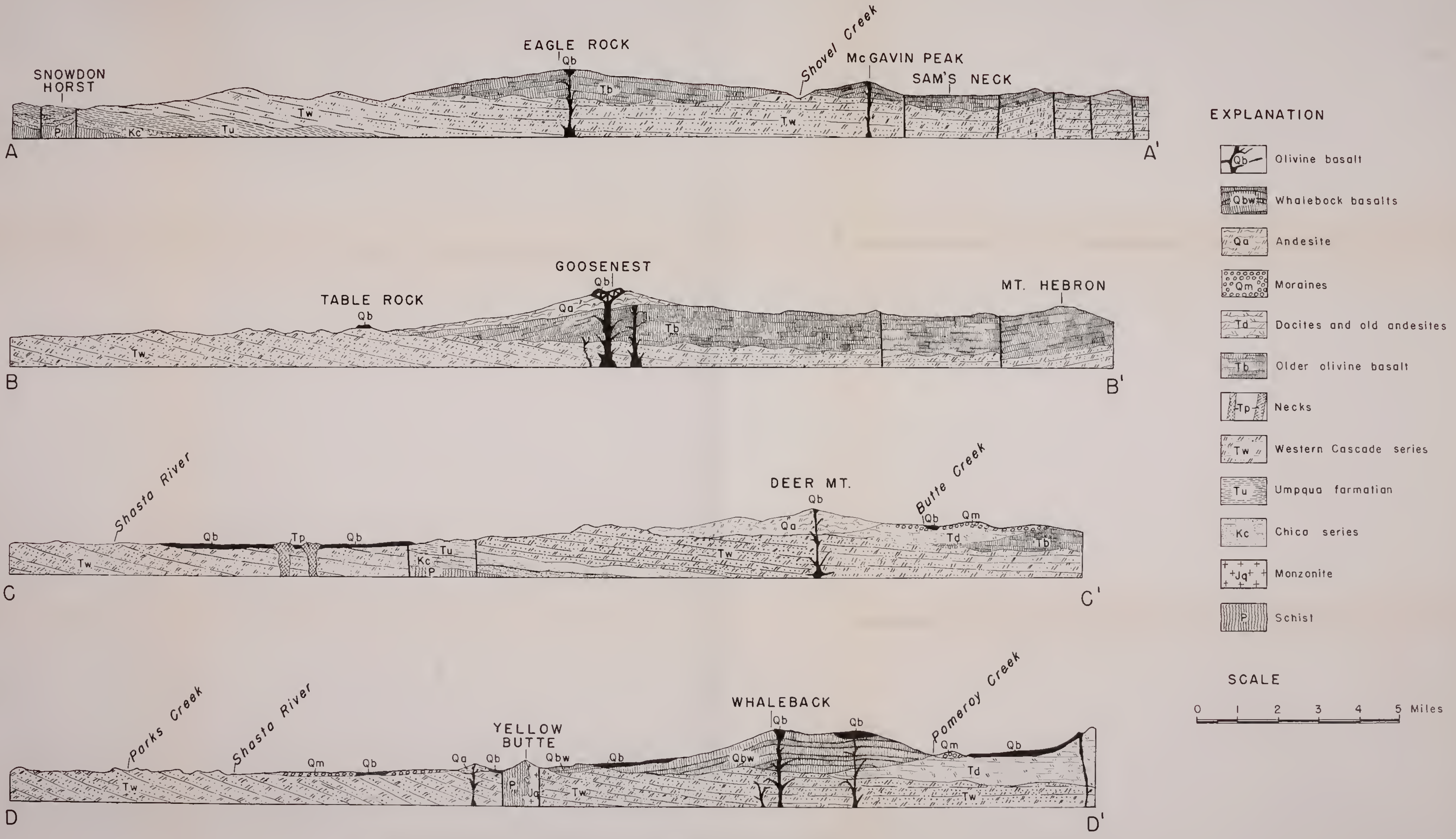
Geology surveyed in 1935-36 and 1948

Scale 1/125000

1 ½ 0 1 2 3 4 5 Miles

1 ½ 0 1 2 3 4 5 Kilometers

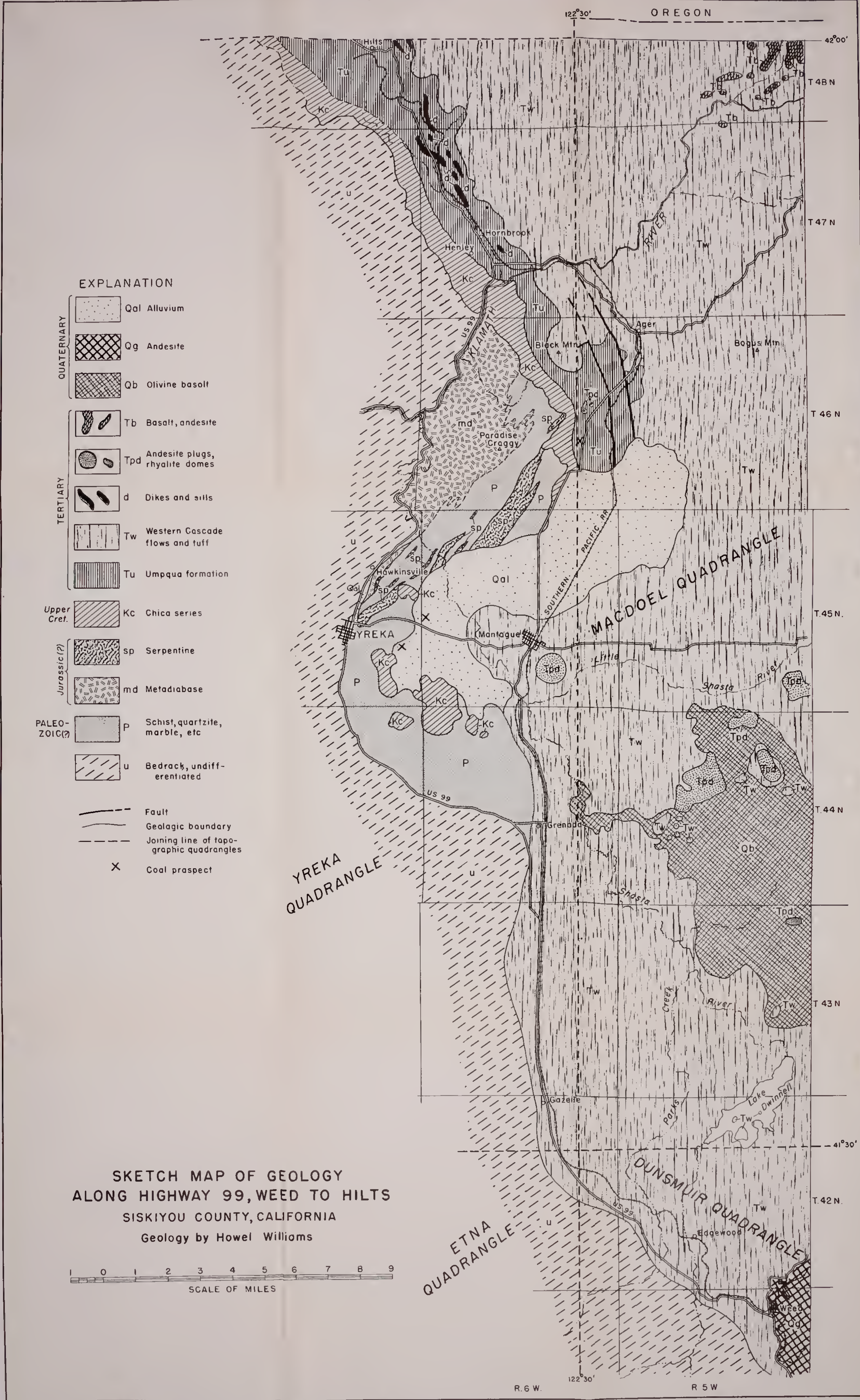
Contour interval 100 feet
Datum is mean sea level



GEOLOGIC SECTIONS ACROSS THE MACDOEL QUADRANGLE

BY

HOWEL WILLIAMS



SKETCH MAP OF GEOLOGY ALONG HIGHWAY 99, WEED TO HILTS

SISKIYOU COUNTY, CALIFORNIA

Geology by Howel Williams

151. PLATE 1

LEGEND

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