# GEOLOGY OF THE CASCADE RANGE AND MODOC PLATEAU *

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Most of the northeastern corner of California, north of the Sierra Nevada, is included in the physiographic provinces of the Cascade Mountains and the Modoc Plateau. The Cascade Range extends northward through Oregon and Washington into British Columbia, and the Modoc Plateau extends into Oregon and southeastward into Nevada. Most of the Cascade Range is a fairly well-defined province, but in northern California the separation between it and the Modoc Plateau becomes indefinite. The block-faulting characteristic of the Modoc region extends into the Cascade Range, and the rocks characteristic of the two provinces are intermingled. The division between the Modoc Plateau and the Great Basin, which borders it on the east, also is vague. Both regions consist of fault-block mountain ranges separated by flat-floored basins, and similar rocks are present on both sides of the boundary.

The outstanding characteristics of the Modoc region are the dominance of volcanism so recent that the constructional volcanic landforms are still clearly preserved and the presence of broad interrange areas of nearly flat basalt plains. It is the basalt plains that have given rise to the designation "plateau"; however, the region as a whole is far from being the high, essentially undiversified plain that the term usually implies.

At the southern end of the region, the rocks of the Cascade Range and the Modoc Plateau overlap the metamorphic and plutonic rocks of the Sierra Nevada; 50 miles to the northwest, similar rocks emerge from beneath the Cascade volcanics at the edge of the Klamath Mountains province. The broad depression extending northeast across the Sierra Nevada-Klamath orogenic belt, originally recognized by von Richthofen (1868), was called the "Lassen Strait," by Diller (1895a, 1897), who believed it to have been a seaway that in Cretaceous time connected the marine basin of California with that of east-central Oregon. Sediments deposited in the southwestern end of the strait are represented by sandstones of the Chico Formation (Upper Cretaceous) which underlie the volcanic rocks of the Cascade Range along the eastern edge of the Sacramento Valley. Probably this depression persisted—though above sea level and disrupted by volcanism and faulting—through much of Tertiary time. Although the plutonic and metamorphic rocks are nowhere exposed within it except in a small area adjacent to Eagle Lake, there can be no serious doubt that they underlie the volcanics throughout the area of the depression.

Throughout most of its extent, from northern California into Washington, the Cascade Range trends slightly east of north. However, at Mount Shasta, 40 miles south of the California boundary, the trend abruptly changes to southeastward. (It is perhaps worth noting that the Sutter Buttes, 150 miles to the south, lie approximately on the extension of the main Cascade trend.) The change in trend of the Cascade Range takes place approximately at the north edge of the "Lassen Strait," where it intersects the Klamath-Sierra Nevada belt; the trend of the southern part of the range is parallel to, and probably controlled by, the underlying Sierra Nevada structures. The southern portion of the range is almost isolated from the northern part by a projection of metamorphic rocks of the Klamath province. Within this portion of the Cascade Range, almost certainly underlain by the older orogenic belt of the Sierra Nevada, the variation in rock types and the incidence of varieties more acidic than andesite appears to be greater than in the northern portion of the range, except for the eastern outliers of the Medicine Lake Highland in California and the Newberry Volcano in Oregon.

Although it is distinctly to the east of the Cascade Range as a whole (fig. 1), the Medicine Lake Highland is generally regarded as an eastward bulge of the Cascade province (Hinds, 1952, p. 129). As Anderson (1941, p. 350) has pointed out, however, the Medicine Lake volcano, like the similarly outlying Newberry Volcano (Williams, 1935), differs somewhat from the typical volcanoes of the High Cascades. Situated in the plateau region, rather than in the Cascade belt of orogenic volcanism, these volcanoes may represent an evolution of stray Cascade-type magmas under different tectonic conditions.

Following Diller's (1895a, 1906) excellent pioneer work in the southeastern part of the region, the amount of geological work that has been done in the Cascade and Modoc provinces of California is surprisingly little. The areas are shown on a scale of 1:250,000 on the Weed, Alturas, Redding, and Westwood sheets of the Geologic Map of California (California Div. Mines, 1958–1964), but published mapping on a larger scale is limited to a few widely separated areas. Within the Cascade Range these include, near the south end, the Lassen Volcanic National Park (Williams, 1932a)

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and the region just to the north (Macdonald, 1963, 1964), and the Macdoel quadrangle (1:125,000) just south of the Oregon border (Williams, 1949). Between these, the region in the immediate vicinity of Mount Shasta has also been described and mapped in a reconnaissance fashion (Williams, 1932b, 1934). The Medicine Lake Highland has been studied and mapped by Anderson (1941), but within the Modoc region proper, the only published mapping on a larger scale is on the area immediately adjacent to Lassen Volcanic National Park (Macdonald, 1964, 1965), in and near the Pit River valley near Alturas (Ford and others, 1963), and near Eagle Lake (Gester, 1962). Unpublished studies have been made of the area south and west of Lassen Volcanic National Park by G. H. Curtis and T. A. Wilson, of the University of California; and reconnaissance studies (unpublished) of many other areas have been made by Q. A. Aune, C. W. Chesterman, T. E. Gay, Jr., P. A. Lydon, and V. C. McMath of the California Division of Mines and Geology. George W. Walker, of the U.S. Geological Survey, who studied parts of the northern Modoc Plateau while preparing the State Geologic Map of Oregon, has generously supplied information for this paper, and information for the section on Cretaceous rocks was supplied by D. L. Jones, of the U. S. Geological Survey.

A generalized geologic map of the northeastern part of California accompanies the article by T. E. Gay, Jr., on the economic mineral deposits of the Cascade Range, Modoc Plateau, and Great Basin regions of northeastern California.

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## CASCADE RANGE

The Cascade Range in Oregon is conveniently divided into the Western Cascade Range and the High Cascade Range (Callaghan, 1933; Peck and others, 1964). The rocks of the Western Cascade Range include lava flows and beds of pyroclastic debris, and in places interbedded nonmarine and shallow marine sediments, gradually accumulated in a slowly sinking trough to a thickness of more than 10,000 feet. Their age ranges from late Eocene to Pliocene (Peck, 1964). In composition, they are predominantly pyroxene andesite but range from olivine basalt to rhyolite. Rocks of the Western Cascade are underlain by Eocene sedimentary rocks of the Umpqua Formation and are unconformably overlain by Pliocene to Recent volcanic rocks of the High Cascade Range. The latter are predominantly pyroxene andesite, but range in composition from olivine basalt to dacite. Early eruptions in the High Cascade were almost wholly basaltic andesite and basalt, producing fluid lava flows that spread to great distances and built a broad, gently sloping ridge that consisted largely of coalescing small shield volcanoes and fissure-type flows. Pyroclastic material was comparatively small in amount. In time, however, the predominant lavas became more siliceous, the proportion of explosive eruption increased, and on the earlier ridge of lavas were built the great composite volcanoes that form the conspicuous peaks of the present Cascade Range. Rarely, domes of dacite were formed. Occasional basaltic eruptions, largely from eccentric and independent vents, appear to have taken place throughout the period of building of the big cones and to have continued afterward.

Volcanic rocks in the Western Cascade Range differ from those of most of the High Cascade Range primarily in greater variety of petrographic types, larger proportion of pyroclastic rocks, and a pervasive chloritic alteration that gives a characteristic greenish hue to most of the rocks. The alteration was probably related to the period of folding and uplift of the Western Cascade, followed by erosion, that preceded the building of the High Cascade, and particularly to the small intrusions of gabbroic to quartz monzonitic composition.

The northern part of the Cascade Range in California is much like that in Oregon. Upper Cretaceous and Eocene sedimentary rocks are succeeded by greenish volcanics of the Western Cascade series which were faulted and tilted eastward and northeastward at about the end of the Miocene (Williams, 1949, p. 14). Erosion destroyed the constructional volcanic landforms and reduced the region to one of rolling hills before renewed volcanism built the High Cascade. Southward the volcanic rocks of the Western Cascade are overlapped by those of the High Cascade, and south of the Shasta region rocks belonging to the Western Cascade series have not been recognized, although volcanic rocks overlain by Pliocene diatomite in the gorge of the Pit River may be equivalent to part of them in age. In the region northwest of Mount Lassen the upper Pliocene Tuscan Formation rests directly on Cretaceous and Eocene sedimentary rocks, and the Western Cascade volcanics are absent.

As in Oregon, the lower part of the High Cascade sequence in California consists largely of pyroxene andesite, with lesser amounts of basalt and minor amounts of hornblende andesite and dacite. Although erosion has destroyed the original topography, these lavas appear to have built a broad ridge with few, if any, big cones. Most of the lavas are probably of latest Pliocene age (Macdonald, 1963). In the region southwest of Lassen Volcanic National Park, however, some of them are of pre-Tuscan age (Wilson, 1961). Continuing volcanism became more concentrated at distinct centers, and more individualized cones were built, some of which are shield volcanoes and some composite cones. The latter included the largest of the volcanic mountains, such as Brokeoff Volcano (Mount Tehama), which collapsed to form the caldera in which

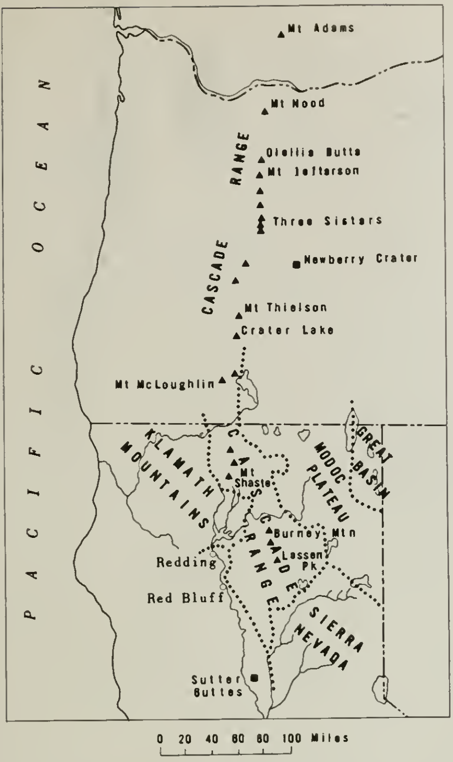


Figure 1. Map of a part of northern California, western Oregon, and southern Washington, showing the principal peaks of the Cascade Range and Sutter Buttes lying farther south along the same trend.

Lassen Peak was later built, Magee Mountain (Crater Peak), Burney Mountain, and Mount Shasta (fig. 1). In the Lassen region, volcanism culminated in the eruption of several dacite domes, some of them only a few hundred years old, and at Medicine Lake, flows and domes of rhyolite obsidian were erupted. Contemporaneously, basaltic volcanism continued with the eruption of such flows and associated cinder cones as the Callahan and Burnt Lava flows near Medicine Lake, and the Hat Creek and Cinder Cone flows in the Lassen region.

With eruptions at Cinder Cone in 1851 and Lassen Peak in 1914–17, and a possible eruption at Medicine Lake in 1910 (Finch, 1928), the Cascade Range of California must be regarded as a region of still-active volcanism.

### Cretaceous and Early Tertiary Sedimentary Rocks

Rocks of Late Cretaceous age are exposed at many places along the east side of the Sacramento Valley from near Folsom, west of the central Sierra Nevada, to the area east of Redding; and from the vicinity of Shasta Valley, northwest of Mount Shasta, to and beyond the northern boundary of the State. In these areas they rest unconformably on the pre-Cretaceous rocks of the Sierra Nevada-Klamath Mountains complex. They have been referred to as the Chico Formation at Chico and Butte Creeks in Butte County and as the Hornbrook Formation in northern Siskiyou County (Popenoe and others, 1960).

The Chico Formation consists of massive gray, buff-weathering, arkosic sandstone, dark-gray to black shales, and beds of conglomerate, particularly near the base. In the type locality at Chico Creek, where it is 4,000 feet thick, it has yielded a varied fauna of ammonites, gastropods, and pelecypods ranging in age from Coniacian to Campanian.

East and north of Redding, a similar thickness of Upper Cretaceous rocks has been described by Popenoe (1943). The lithologies present are much like those at Chico Creek, but although the time of deposition of the rocks in the two areas overlaps considerably, the section at Redding spans a slightly older segment of the Late Cretaceous.

In the Hornbrook area near the California-Oregon boundary, the Cretaceous rocks consist of about 5,000 feet of conglomerate, sandstone, and siltstone. The oldest unit, which rests unconformably on granitic and metamorphic rocks, contains marine fossils (Turonian to Coniacian), but part of the overlying conglomeratic sandstone is nonmarine. These rocks are in turn overlain by 5,000 feet of marine siltstone, with some sandy interbeds. This silty sequence was long regarded as a part of the widespread Eocene Umpqua Formation, but it has been found to contain Late Cretaceous fossils in its upper part (Jones, 1959). About 5 miles south of Ager, in exposures near the western edge of the Copco quadrangle, the section contains a bed of coal, in places as much as 6 feet thick, that was at one time mined. Fossils discovered in overlying shales confirm the Cretaceous age of the coal beds, formerly regarded as Eocene. Thus, no rocks that can be positively assigned to the Umpqua Formation of early to middle Eocene age (Baldwin, 1964) are known in the California part of the Cascade Range or Modoc Plateau provinces. The Late Cretaceous in this area was a period of shallow marine sedimentation with some nonmarine deposition, in part on swampy flood plains in the northern area. Marine deposition in northeastern California terminated in the latest Cretaceous, and there is no depositional record for the Paleocene or earliest Eocene.

Deposition in late Eocene time is recorded by the Montgomery Creek Formation (Williams, 1932a; Anderson and Russell, 1939), which was originally included by Diller (1895a) in the Ione Formation. The Montgomery Creek Formation is exposed along the east side of the Sacramento Valley from near Shingletown, 25 miles east-southeast of Redding, northward

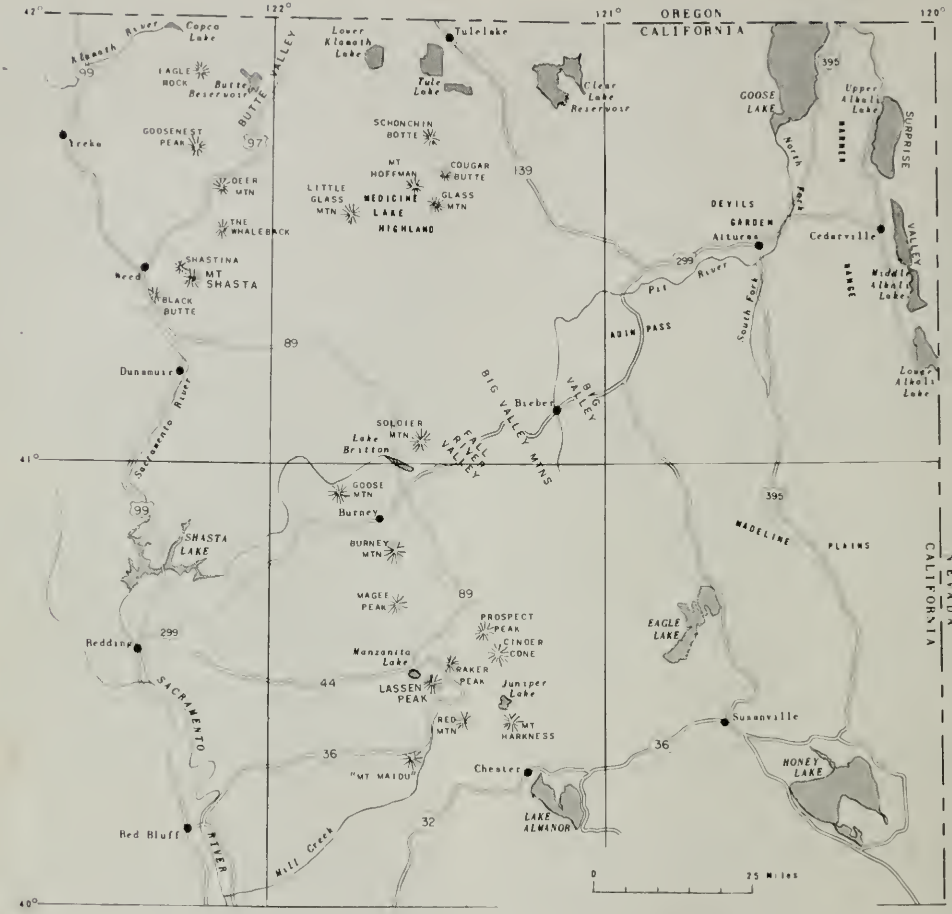


Figure 2. Index map of northeastern California showing the principal physiographic features referred to in the text.

for about 50 miles to the upper drainage basin of Kosk Creek in the Big Bend quadrangle. It is extensively exposed along the Pit River near Big Bend, and some of the best and most easily accessible exposures are along Highway 299 (fig. 2) just east of Montgomery Creek, where sandstones and conglomerates in a big highway cut contain fossil leaves. In most places the Montgomery Creek Formation consists predominantly of pale-gray massive sandstone, weathering to buff, that is locally much channeled and cross-bedded and commonly contains scattered pebbles and pebbly lenses. Thick beds of conglomerate, and less commonly of silty shale, are present in places. Locally, as along Coal Creek in the Whitmore quadrangle, the formation contains thin beds of poor-grade coal that have been mined to a small extent in the past. Fragments of petrified wood are common in some areas. The sandstones are poor in ferromagnesian minerals, and in general are weakly cemented. Their weak consolidation results in poor exposures; and where valleys have been cut into them, the poor consolidation commonly produces extensive landsliding of overlying more resistant rocks such as breccias or andesitic lava flows of the upper Pliocene Tuscan Formation. Typically, the Montgomery Creek Formation rests unconformably on Upper Cretaceous sedimentary rocks and is overlain unconformably by Pliocene volcanic rocks.

Figure 3. Index map of same area as figure 2, showing location of quadrangles and principal geographic features mentioned in the text.

### Western Cascade Volcanic Series

The rocks of the Western Cascade volcanic series form a nearly continuous belt extending along the western foothills of the Cascade Range for 45 miles south of the State boundary, and scattered outcrops for another 10 miles. They are exposed along Highway 99 just west of Weed, but are better seen along the road extending eastward along the Klamath River from Hornbrook to Copco Lake. The following description is largely summarized from the report by Williams (1949, p. 20–32).

Near the State boundary, the exposed thickness of the Western Cascade volcanics is not less than 12,000 feet, and may be as much as 15,000 feet. In the northern part of the Yreka quadrangle, a few thin beds of volcanic conglomerate and sandstone of the Colestin Formation (upper Eocene) rest unconformably on the Hornbrook Formation at the base of the Western Cascade series, but farther south these are absent and the lowest lavas rest directly on the Hornbrook Formation or overlap it to rest on the pre-Cretaceous plutonic and metamorphic basement. A few lenses of tuffaceous sandstone and volcanic conglomerate are interbedded with the volcanics at higher stratigraphic levels, and coal and carbonaceous shale are present east of Little Shasta. The volcanic rocks include both lava flows and fragmental deposits, the latter being in part direct products of volcanic explosion and in part mudflow deposits.

The lava flows are mostly pyroxene andesite, generally with hypersthene more abundant than augite. Some contain a small amount of olivine, commonly replaced by serpentine or iddingsite, or by a mixture of magnetite and hematite or goethite. A small amount of cristobalite or tridymite generally is present in the groundmass. Most flows are between 10 and 30 feet thick, but a few exceed 100 feet. Most are dense to sparingly vesicular, and most have a well-developed platy jointing that results from shearing in the flow as slight movement continues during the last stages of consolidation. Hornblende andesites and hornblende-bearing pyroxene andesites are relatively rare, as are flows of dacite. The Western Cascade lavas in northern California are less altered than many of those in Oregon, possibly, Williams suggests, because of the absence of subvolcanic dioritic stocks and related mineralized belts. Particularly in the upper part of the series, however, many of the andesites are propylitized, the feldspars being partly altered to kaolin and the pyroxenes replaced by calcite, chlorite, and limonite. In many andesites, veins and amygdules of opal and chalcedony are abundant, and silicified wood may be found in the intercalated tuffs, as at Agate Flat, in the north center of the Copco quadrangle, just south of the State boundary.

Pyroclastic rocks include well-stratified andesitic tuff-breccias and lapilli tuffs, basaltic agglomerates composed of rounded lapilli and bombs, and tuffs of andesitic, basaltic, dacitic, and rhyolitic composition. Rhyolitic tuffs are found chiefly in the upper part of the series. Well-bedded rhyolitic lapilli tuffs of air-laid origin reach a thickness of nearly 500 feet near the head of Shovel Creek in the northern part of the Macdoel (1:62,500) quadrangle; and dense dust-textured tuffs reach a similar thickness near the head of Little Bogus Creek in the center of the Copco quadrangle. Near Bogus School a bed of rhyolitic tuff, traceable for more than 5 miles, varies from an incoherent rock, rich in pumice fragments up to an inch long, to a compact crystal-vitric tuff nearly devoid of pumice fragments. In places, particularly near the base, it is streaky and welded. The rock is an ignimbrite formed by an incandescent ash flow. A quarter of a mile north of Bogus Creek, a vertical dike of glassy rhyolite 10 feet thick, closely resembling the dense crystal-vitric tuff, cuts the bottom of the bed. This dike is considered to be the filling of a fissure that gave vent to the tuff in the same manner as the eruption of the "sand flow" of 1912 in the Valley of Ten Thousand Smokes in Alaska (Williams, 1949, p. 25). Welded dacite tuff near the eastern foot of Miller Mountain, in the west-central part of The Whaleback quadrangle, is considered by Williams to belong to the Western Cascade series and to unconformably underlie basalt of the High Cascade series.

At Sheep Rock, south of Miller Mountain, beds of coarse andesitic tuff-breccia containing angular to subangular blocks up to 4 feet across in a tuffaceous matrix reach a thickness of 1,600 feet. Individual layers, some of them more than 100 feet thick, show only a very crude bedding. The deposits resemble those of the Tuscan Formation in the Cascade Range and the Mehrten Formation (Miocene and Pliocene) in the Sierra Nevada (Curtis, 1957), and like them, are interpreted as being the products of volcanic mudflows. Similar deposits are found northwest of Little Shasta, on the south side of Bogus Mountain, and along the Klamath River south of Brush Creek, in the northwest portion of the Copco quadrangle.

Several rhyolite domes are found in the vicinity of Little Shasta, and volcanic necks and plugs of andesite and basalt occur near the lower end of Copco Lake and in Shasta Valley. Two necks at Agate Flat are oval in plan, elongated north-south, and approximately 2,000 by 1,000 feet across. One of the andesite necks, at the hairpin turn of the Klamath River a mile below the Copco Dam, is noteworthy for the presence of aegirine in veinlets that also contain zeolites and magnetite and as an alteration product of other pyroxenes close to the edge of the veinlets (Williams, 1949, p. 29). Another of the necks has marginal ring dikes that dip outward at angles of 60°–80°.

Near the end of the Miocene, the entire Cascade belt is believed to have been upheaved, perhaps partly by arching, but partly by roughly north-south faulting that produced high east-facing scarps like the one 2,000 feet high described by Thayer (1936, p. 708) near Mount Jefferson in Oregon. Similar fault scarps are believed by Williams (1942, p. 29) to have formed and been buried by later High Cascade lavas near Crater Lake, Oregon; others may have formed in the region just north of Mount Shasta (Williams, 1949, p. 52). Still other faults formed horsts along the eastern side of Shasta Valley and one bordering Shasta Valley near Yellow Butte (Dwinnell Reservoir quadrangle) must have had a throw of more than 10,000 feet (Williams, 1949, p. 53). Whether any corresponding displacements took place in the portion of the Cascade Range south of Mount Shasta is not known. The fact that the northwesterly trend of this portion of the range coincides with the direction of Sierra Nevada-Klamath Mountains structures that are believed to underlie it suggests that south of Mount Shasta the Cascade Range may have shared the history of uplift of the Sierra Nevada, rather than that of the main, northern portion of the Cascade Range.

Some time after the upheaval of the main Cascade Range, fissures were opened on or near the crest of the ridge, and along them new magma rose to the surface to build the High Cascade volcanoes during Pliocene to Recent times (Williams, 1949, p. 35). The new vents appear to have been located somewhat to the east of those that supplied the lava of the Western Cascade Range (Peck and others, 1964, p. 50). The building of the Cascade Range south of Mount Shasta must have been coeval with that of the High Cascade Range farther north.

### Tuscan Formation

The Tuscan Formation is exposed continuously for 65 miles along the east side of the Sacramento Valley, from near Oroville to 15 miles north of Red Bluff, with smaller isolated areas east of Redding. It has been shown by Anderson (1933a) to consist largely of breccias formed by lahars, or volcanic mudflows. The eastern part of the Tuscan consists almost entirely of tuff-breccia, in beds ranging from about 40 to 100 feet thick, and the entire accumulation averages about 1,000 feet in thickness. Along Mill Creek Canyon, southwest of Lassen Peak, its thickness is about 1,500 feet (Q. A. Aune, oral communication, 1965). Toward its western edge, interbedded volcanic conglomerates, sands, and tuffs appear, and still farther west it interdigitates with the strictly sedimentary Tehama Formation (Anderson and Russell, 1939, p. 232). Its southern portion rests on the western slope of the Sierra Nevada and overlaps the Sierran metamorphic and plutonic complex, but its northern portion forms part of the western slope of the southern Cascade Range.

Interbedded in the lower part of the Tuscan Formation in the southern part of the area, east of Red Bluff, and with the Tehama Formation on the west side of the Sacramento Valley, is 40 to 100 feet of gray, white, or pink dacite tuff containing fragments of pumice up to a few inches across in a matrix of glass and crystal shards. The massive and unsorted character of the deposit and the cleanness of the pumice vesicles indicates the ash-flow origin of the deposit. Even clearer is the evidence along Bear Creek, in the Millville quadrangle, east of Redding, where the tuff is in places more than 200 feet thick and much of it is thoroughly welded, with the elongate black glass "flames" characteristic of ignimbrite. This tuff is known as the Nomlaki Tuff Member (Russell and VanderHoof, 1931, p. 12–15). Vertebrate fossils in the Tehama Formation 10 feet above the Nomlaki indicate a late Pliocene age for the Tehama and Tuscan Formations and the intercalated Nomlaki. This age is confirmed by a potassium-argon age of 3.3 m.y. for the tuff along Bear Creek (Everndon, et al., 1964). It appears probable, however, that the tuff along Bear Creek was derived from a different source than that farther south.

Individual blocks in Tuscan breccia generally range from 1 to 6 inches across, but scattered blocks are commonly as much as 5 feet thick. Many are vesicular, and most were quite certainly derived from lava flows. Erosion of the formation results in removal of the finer material and concentration of the larger blocks on the surface, forming the broad stony plains crossed by the highways running northeastward from Chico and eastward from Red Bluff and Redding. Cross sections of the breccias are well displayed near Highway 32, along Deer Creek northeast of Chico, along Highway 36 east of Red Bluff, and less spectacularly along Highway 44 and the Millville-Whitmore Road east of Redding.

In the main southern area the blocks in the breccia are predominantly basalt, with lesser amounts of andesite; but in the smaller northern area, they are predominantly andesitic and dacitic, except locally along Bear Creek, where basalt is again abundant (Anderson, 1933a, p. 228). The difference in the prevalent type of rock among the blocks suggests different sources for the breccias of the southern and northern areas, and Lydon (1961) believes that the Tuscan Formation is derived from at least four different sources: one near Butt Mountain, 9 miles southwest of Lake Almanor, and nearly due east of Red Bluff; one near Mineral, 10 miles south-southwest of Lassen Peak; one east of Whitmore, 30 miles east of Redding; and another, less certain, a few miles farther north, west of Burney. All of these sources lie within the Cascade Range, and the Tuscan Formation, including the Nomlaki Tuff Member, almost surely is to be regarded as a unit within the High Cascade volcanic series. Along the edge of the Sacramento Valley east of Redding, it is the oldest unit, resting directly on the Montgomery Creek and Chico Formations, but in the Mineral area it is underlain by a thin series of basic lava flows.

In the area east of Redding, the Tuscan Formation, with its interbedded late Pliocene (3.3-m.y.) Nomlaki Tuff Member, serves to limit the maximum age of the overlying lavas, and these in turn indicate a limiting age for the widespread Burney (or so-called Warner) Basalt in the part of the Modoc Plateau just to the east. In other areas, however, the Tuscan Formation may range through a considerable age span. Q. A. Aune (oral communication, 1965) states that along Antelope Creek, in the Red Bluff quadrangle east of Red Bluff, the upper layers of the Tuscan Formation are nearly horizontal, whereas the lower layers are deformed nearly as much as the underlying Cretaceous strata. He suggests that the lower part of the Tuscan in that area may be considerably older than the late Pliocene age generally accepted for the formation.

### High Cascade Volcanic Series

The time of beginning of High Cascade volcanism is difficult to date precisely. In the region north of Mount Shasta the oldest of the High Cascade rocks are younger than the Miocene rocks of the Western Cascades and older than other rocks that are in turn overlain by Pleistocene glacial moraines. They have been referred to the Pliocene, but there is no assurance that the moraines in question are not wholly of late Pleistocene age, and hence that the older lavas themselves may not have been erupted in the Pleistocene. Near the south end of the Cascade Range, northwest of Lassen Peak, andesite lava flows of the High Cascade rest on the Tuscan Formation (Macdonald, 1963), which is of latest Pliocene age (Axelrod, 1957,

p. 27). These andesites cannot, therefore, be older than latest Pliocene. They have, however, been much eroded, and the original constructional volcanic landforms on them have been destroyed to a considerably greater degree than on the oldest High Cascade lavas between Mount Shasta and the Oregon boundary. Consequently, it appears unlikely that the latter are older than latest Pliocene, and they are more probably of Pleistocene age. The basic lava flows that underlie the Tuscan formation near Mineral are probably the oldest exposed rocks in the High Cascade Range of California. Conversely, only relatively minor amounts of volcanic rock appear to be later in age than the youngest glaciation. The building of the High Cascade took place largely in Pliocene and Pleistocene times.

Williams (1949, p. 35) writes,

> "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 [between Mount Shasta and the Oregon border in the Macdoel and The Whaleback quadrangles] 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 volcanoes include Miller Mountain, Ball Mountain, and the Eagle Rock shield. On the eastern edge of the area a series of similar broad cones, including Mount Hebron, south of Butte Valley, the McGavin Peak and Secret Spring Mountain, north of Butte Valley, are cut by faults of large displacement that represent the edge of the block-faulted Modoc Plateau. The only signs of explosive activity are a few thin beds of cinders intercalated with the flows on Secret Spring Mountain, and the remains of cinder (scoria) cones on the summits of Horsethief Butte, Ball Mountain, and a small shield north of the Copco Dam. Slightly younger than the basaltic shields is a series of thick flows of hornblende andesite and dacite(?) erupted from the Haight Mountain volcano, in the Bray quadrangle, just northeast of Mount Shasta, probably soon followed by the pyroxene andesites of Deer Mountain, Willow Creek Mountain, and the early andesite flows of Mount Shasta. These rocks contain abundant phenocrysts of hypersthene, augite, and labradorite in a pilotaxitic groundmass, with a little tridymite and cristobalite lining cavities. They resemble the principal types of andesite composing many of the big cones of the High Cascade (Williams, 1949, p. 40). Still later, eruptions of andesite built the Goosenest volcano, olivine basalt flows built the steep-sided cone of The Whaleback volcano, and finally floods of olivine basalt issued from fissures to pour down the valley of Alder Creek and spread over large parts of the floors of Butte and Shasta Valleys. Small flows of this group dammed the Klamath River to form a lake, at least 35 feet deeper than the present Copco Lake, whose shorelines are marked by conspicuous deposits of diatomite.

The history of Mount Shasta itself will be outlined on a later page.

The sequence of events in the area just north of Lassen Volcanic National Park is in general much the same as that deduced by Williams in the region north of Mount Shasta, outlined above. The earliest lavas, which rest on breccias of the Tuscan Formation, are pyroxene andesites associated with small amounts of hornblende andesite and dacite. These masses, presumably of latest Pliocene age, are deeply eroded, with resultant complete obliteration of constructional forms, and the position of former vents is indicated only by a few small intrusive plugs and a few cindercone remnants. The predominant lavas are two-pyroxene andesites, commonly with small phenocrysts of feldspar and often of hypersthene. Scattered small phenocrysts of olivine are present in some flows, and at Latour Butte blocky augite phenocrysts as much as 1 cm long are abundant. These andesites were gently folded on east-northeast-trending axes and were slightly eroded before they were covered locally by olivine-bearing basalts and basaltic andesites considered to be of very early Pleistocene age.

Both the andesites and the basalts were then broken by a series of northwest- to north-trending faults. Next came a succession of eruptions of basalt, basaltic andesite, and andesite that built a series of small shields and lava cones. Some of the andesites, such as those of Table and Badger Mountains, at the north edge of Lassen Volcanic National Park, are very siliceous despite their very dark color and decidedly basaltic aspect in the field. The Burney Basalt, a "plateau" basalt, rests against the base of the Badger Mountain shield. Next came a series of eruptions of andesite that built somewhat larger cones, including Crater Peak (generally known locally as Magee Mountain), and the Brokeoff (Tehama) Volcano that later collapsed to form the caldera in which Lassen Peak and its associated domes were built. The construction of the big composite cones was followed by the extrusion of domes and thick flows of dacite.

Through later Pleistocene and Recent time, basalt, basaltic andesite, andesite, and dacite have been erupted more or less simultaneously. Many of the basalt flows are of very large volume and extent, and in range of types are identical to the flows of the Modoc region to the northeast. One such flow, near Whitmore, covers an area of about 25 square miles. Another extends nearly 30 miles, from near the northwest corner of Lassen Volcanic National Park to about 2 miles southeast of Millville, nearly parallel to Highway 44 for most of that distance. It covers an area of more than 50 square miles; and its volume exceeds 1 cubic mile, and may be as great as 2.

A feature of this region that deserves special mention is the very widespread occurrence of quartz xenocrysts in the lavas. They are most common in the late basalts, such as the well-known quartz basalt of Cinder Cone in the Prospect Peak quadrangle (Finch and Anderson, 1930), but they are found in both basalts and andesites ranging in age from late Pliocene to Recent. They can be found in the basalt along Highway 89 in the pass just north of the Manzanita Lake entrance to Lassen Volcanic National Park and are abundant at Red Lake Mountain, a mile to the northwest. Not uncommonly they are several inches across, and some of them clearly show the comb structure characteristic of many quartz veins. There seems to be little question that they are fragments of veins picked up by the magma in its rise through the underlying basement of crystalline rocks. Some show no signs of reaction with the enclosing magma, but others are rounded and enclosed in thin reaction rims of pyroxene.

The region south and west of Lassen Volcanic National Park has been studied and described by T. A. Wilson (1961). After the deposition of the Tuscan breccias a big strato-volcano, named by Wilson Mount Maidu, rose around a vent located at Battle Creek Meadows, near Mineral, in the Lassen Peak quadrangle. The growth of the cone was contemporaneous with that of the Brokeoff Volcano, just to the northeast. Early eruptions of basaltic andesite were followed by later ones of pyroxene andesite and dacite. This was followed, some 1½ m.y. ago (potassium-argon age by G. S. Curtis), by the eruption of two enormous flows of rhyolite from fissures on the lower slopes of the composite cone. One flow is exposed along Blue Ridge and Snoqualmie Gulch, 7 miles northwest of Mineral, and the other on the Mill Creek Plateau, 5 miles southeast of Mineral, but both are accessible only by minor country roads. These remarkable flows cover an area of about 78 square miles. Their average thickness is nearly 500 feet and their maximum thickness exceeds 800 feet. The total volume is about 7.6 cubic miles! They were followed by eruption of glowing dacite avalanches, probably from the same fissures that gave vent to the more westerly of the rhyolite flows. These avalanche deposits of pumice tuff-breccia range from 100 to 200 feet thick. Their present area is about 21 square miles, but large amounts of the easily eroded material have been stripped away, and the original area was probably two or three times as great. The original volume of the avalanche deposits was probably at least 1½ cubic miles. With the eruption of more than 8 cubic miles of rhyolite and dacite magma from its lower flanks, it is small wonder that the summit of Mount Maidu volcano collapsed to form a caldera! Later came a series of basalt eruptions that built shield volcanoes with summit cinder cones, or cinder cones with associated lava flows. One of the latter is Inskip Hill, the edge of which is crossed by Highway 36 about 20 miles east of Red Bluff.

Little information is available on the part of the Cascade Range between Mount Shasta and the row of quadrangles (Whitmore, Manzanita Lake, and Prospect Peak) which include the northern part of Lassen Volcanic National Park. The stratigraphic relationships appear to be much like those described for the parts of the range to the north and south except that in part the basic lavas rest directly on the pre-Cretaceous rocks of the Klamath Mountains. Along Highway 299 west of Burney, on the Hatchet Mountain grade that ascends the fault scarp at the east side of the range, are exposed a series of mudflow breccias which appear to be too high in the volcanic sequence to be equivalent to the Tuscan Formation. On the same highway, 0.2 mile uphill from the 4,000-foot altitude marker, massive glowing-avalanche deposits contain numerous fragments of white to cream-colored pumice up to 6 inches long. Similar deposits, exposed for half a mile westward, commonly contain many fragments of andesite and dacite. The same or similar beds, one of them containing many dark irregular bombs and lapilli of andesitic cinder, are conspicuously displayed in roadcuts and a quarry just west of Hatchet Mountain summit, interbedded with flows of andesite. These rocks appear to be of about the same age as the folded, very late Pliocene volcanic rocks in the Manzanita Lake quadrangle.

The Hatchet Mountain fault, west of Burney, appears to be older than the basaltic shield of Goose Mountain (northeast Montgomery Creek quadrangle), which is built against the base of the scarp. The cone of Burney Mountain, one of the major peaks in this part of the range, appears to be built almost entirely of block-lava flows of basaltic andesite, though it may, like Magee Mountain just to the south, have a pyroclastic core (Macdonald, 1963). Burney Mountain shows no sign of having been glaciated, and at least its carapace is probably of Recent age, though it appears to be older than the twin cinder cones and associated basalt lava flows at its southeast base.

Just north of the Pit River, the andesites and basalts mapped by Powers (1932, pl. 1) along the east edge of the Cascade Range as his massive lava group also appear to be equivalent, at least in part, to the late Pliocene volcanic rocks of the Manzanita Lake and Whitmore quadrangles. Their original surface forms have been destroyed by erosion and they have been severely glaciated, but they are less deformed than the nearby rocks of probable Miocene age of the Cedarville Series of Russell (1928) in the Modoc Plateau and have been regarded by Powers (1932, p. 259-260) as probably of Pliocene age.

A series of interbedded basaltic and andesitic lava flows, mudflow deposits, volcanic sediments, and a little diatomite are exposed along the gorge of the Pit River west of Lake Britton (Aune, 1964, p. 187) and dip in general 15°–30° northeastward. They are overlain unconformably by diatomaceous sediments deposited in a lake that occupied the site of the present Lake Britton but was considerably more extensive. According to G. Dallas Hanna, the diatoms in these sediments are of Pliocene age, probably not younger

Photo 1. Mount Shasta. *Photo by G. Dallas Hanna.*

than middle Pliocene (Aune, 1964, p. 187). On that basis, Aune infers a Miocene age for the volcanic rocks along the Pit River gorge. The latter rocks resemble those of the Cedarville Series a few miles to the east, in Fort Mountain (southeastern Pondosa quadrangle) and its southward continuation, and probably should be correlated with them. Further work probably will demonstrate that the late Pliocene and Pleistocene volcanics of the Cascade Range have here buried one of the fault blocks of the Cedarville Series characteristic of the Modoc province.

*Mount Shasta.*—The beautiful double cone of Mount Shasta is the largest of the Cascade volcanoes. From a base about 17 miles in diameter, it rises to an altitude of 14,162 feet, some 10,000 feet above the average level of its surroundings. Its volume is about 80 cubic miles. The slope of the cone diminishes from about 35° near the summit to 5° near the base. The geology of Mount Shasta has been described by Diller (1895b) and Williams (1932b, 1934); the following account is taken largely from the papers by Williams.

To the south and west, the lavas of Mount Shasta rest in part on older (late Pliocene?) andesites of the High Cascades and slightly altered volcanics of the Western Cascades, and in part on metamorphic and plutonic rocks of the Klamath Mountains complex. Haystack Butte, in the southeast corner of the Dwinnell Reservoir quadrangle, 10 miles north-northwest of the summit of the mountain, is a steptoe of the latter rocks projecting through basalt and andesite flows of Mount Shasta. To the east, the Shasta flows disappear beneath a cover of later volcanics.

The main cone of Mount Shasta is so young that only its outermost part is exposed by erosion. The deepest canyon, that of Mud Creek, on the southeast flank, has cut into it only about 1,500 feet. The visible portion of the cone consists, according to Williams, almost entirely of massive, poorly banded, moderately vesicular lava. Individual flows attain a thickness of 200 feet but average only about 50 feet; apparently all originated from the single central vent. Block lava and aa flows are rare and largely confined to the upper part of the cone. The lavas of the basal part of the cone are predominantly basaltic andesite, whereas the later lavas of the upper part are predominantly pyroxene andesite, with a lesser amount of dacite. Some of the latest flows contain basaltic hornblende, and the very summit of the mountain consists of solfatarized dacite. Pyroclastic materials are present only in small proportion. Fragmental beds in the walls of Mud Creek Canyon, which are among the oldest exposed rocks of the cone, appear to be mudflow deposits, and Williams comments (1934, p. 231) that mudflows must have been numerous and extensive during the rise of the main cone of Shasta, in the Pleistocene Epoch, when much of its surface was covered with glaciers.

Late in the history of the volcano, a fissure opened across the cone in a nearly north-south direction, and along it eruptions formed a series of domes and cinder cones with associated lava flows. Gray Butte and the McKenzie Buttes, on the south side of the mountain, are domes belonging to this series, and nearby Red Butte and Signal Butte (formerly called Bear Butte) are cinder cones. Gray Butte is hornblende-pyroxene andesite, and the McKenzie Buttes are glassy dacite. On the north flank of the mountain, in northwestern Shasta quadrangle, the two prominent hills just southwest of North Gate are dacitic domes on the same line of fissuring, and North Gate itself marks the vent of a young flow of basalt that overlaps the western edge of The Whaleback shield volcano. About 2.5 miles east-northeast of North Gate, a mile south of Military Pass, is the steep blocky front of a slightly older flow of andesite that originated on the upper slope of the main cone in the vicinity of the present Hotlum Glacier.

At the southwestern base of Mount Shasta, just west of the line of vents mentioned above, is Everitt Hill, a shield volcano with a small cinder cone at its summit. Flows of basaltic andesite from this vent extend southwestward down the canyon of the Sacramento River for more than 40 miles (Williams, 1934, p. 235). The columnar-jointed lava, at places overlying river gravels, is well exposed in cuts along Highway 99. At Shasta Springs, in the northeastern corner of the Dunsmuir quadrangle, a large volume of water issues from the base of this flow, where it is perched by underlying stream-laid sediments.

Also very late in the history of the volcano, and possibly at about the same time as the development of the north-south fissure, an east-west fissure opened on the western flank of the mountain. Eruptions along this fissure built a small lava-and-cinder cone a mile west of the summit, and shortly afterward short thick flows of pyroxene andesite began to erupt from another vent half a mile farther west, building the lateral cone of Shastina, which eventually grew to nearly rival the main cone in height. The last eruptions of Shastina built two small domes and a small dikelike plug of hornblende andesite within the crater. Extending from a deep notch in the crater rim down the western slope of Shastina is Diller Canyon, a V-shaped gash averaging about a quarter of a mile across and as much as 400 feet deep. Williams (1934, p. 236) suggests that it may have been formed by violent downward-directed explosions and glowing avalanches resembling those of Mount Pelée in 1902, which followed the rise of the domes in the crater. The explosions and resulting avalanches may have been guided by a preexisting fracture. The sides of the canyon and the surface near its distal end are mantled with angular blocks of hornblende andesite like that of the domes, almost certainly deposited by avalanches, but at temperatures too low to produce bread-crusting of the blocks or alteration of the hornblende crystals on their surfaces (Williams, 1934, p. 236). No doubt the avalanches modified the form of the mountain slope, but whether they alone could have formed the great gash remains in doubt.

The domes in the crater of Shastina are of postglacial age, their surfaces being wholly unmodified by ice action, although most of the surface of Shasta and Shastina was covered by Pleistocene glaciers. On the west, ice descended to the level of the valley at the base of the mountain, and on the east ice from the Shasta center extended outward over the Modoc Plateau. Evidence of only one stage of glaciation has been recognized, but since the mountain was probably in active growth throughout the Pleistocene, deposits of earlier glacial stages have probably been buried by later lavas.

At present, the Wintun Glacier, on the east side of the mountain, extends down to an altitude of about 9,125 feet, and on the northwest slope the Whitney Glacier reaches about 9,850 feet. The glaciers of Mount Shasta have been shrinking rapidly during recent decades. In 1934 Williams estimated that they covered an area of slightly more than 3 square miles, whereas in 1954 they covered only about 2 square miles. In 1895 Diller reported the length of the Konwakiton Glacier, on the south slope of the mountain, to be about 5 miles, but its present length is scarcely more than 0.25 mile. Edward Stuhl estimated that during the year 1924 alone the length of the glacier decreased three-eighths of a mile (Williams, 1934, p. 252). Rapid melting of the snow and ice during dry years results in torrents of water which issue from the snout of the glacier and rush down the canyon of Mud Creek. Undermining of the canyon walls, formed of old mudflow breccias, sometimes results in landslips that form temporary dams, which may then be breached to release floods that travel down the canyon to overflow and spread mudflow debris over the lower slopes of the mountain.

Probably even later than the domes in the crater of Shastina is a series of block-lava flows of pyroxene andesite erupted from progressively lower vents on the west flank of the cone, covering an area of nearly 20 square miles. Like the summit domes, these flows are of postglacial age, one of the earliest of them issuing from vents in the side of the terminal moraine of the Whitney Glacier. In the walls of Whitney and Bolam Canyons, moraines are exposed beneath the lava flows. The surfaces of the flows are almost perfectly preserved, and the youngest of them probably are not more than a few hundreds of years old.

At the west-southwest base of Mount Shasta, between the towns of Mount Shasta and Weed, Highway 99 skirts the base of Black Butte, a dome of hornblende andesite. The mountain is about 2,500 feet high and 1.5 miles in basal diameter, and owes its almost perfectly conical form to the great banks of crumble breccia that completely mantle the solid core of the dome except for a few crags near the top.

The latest eruptions of Mount Shasta appear to have been from the summit vent of the main cone; they produced a deposit of hypersthene andesite pumice and cinder containing blocks, lapilli, and bombs of dark glassy andesite. This deposit mantles the cirque heads and forms the Red Banks on the south side of the summit crater (Williams, 1934, p. 231). The final explosion, which covered the upper part of the mountain with a thin layer of brown pumice, may have taken place in 1786, when an eruption apparently in the general location of Mount Shasta was recorded by La Perouse as he cruised along the coast (Finch, 1930).

Photo 2. Shasta Mountain. From the Wilkes Exploring Expedition, in the mid–19th century.

At present, the summit crater of Mount Shasta is filled by a snowfield about 600 feet across, with a small acid hot spring at its margin. When the mountain was first climbed by E. D. Pearce in 1854, there were about a dozen such springs, emitting prominent clouds of steam (Williams, 1934, p. 239). The spring water contains free sulfuric acid, and ranges in temperature between about 166°F and 184°F, depending on weather and the amount of dilution by melt water from snow. The rocks within and around the crater are partly opalized and otherwise altered by solfataric action.

*Lassen Peak region.*—Many of the rocks and structures of the region around Lassen Peak are directly continuous with those of the Manzanita Lake and Prospect Peak quadrangles (Macdonald, 1963, 1964), mentioned above. Although the oldest rocks of the Lassen region are isolated from those to the north by intervening younger volcanics, they can be correlated with them with considerable certainty. The rocks named the Juniper Andesites by Williams (1932a) are similar petrographically and in degree of deformation and erosion to the late Pliocene andesites of the more northerly region, and both are clearly overlain by the almost-continuously-exposed Eastern Basalts. The earlier Willow Lake Basalts of Williams (1932a) are probably equivalent to Pliocene volcanic rocks in the region northeast of Lassen Volcanic National Park.

The geology of Lassen Volcanic National Park has been studied in detail by Williams, and we cannot do better than to quote his extended summary (Williams, 1932a, p. 216–219):

> "The earliest activity seems to be recorded in the Willow Lake basalts exposed along the southern border of the Park, but of the source of these lavas nothing is at present known. They were followed by the eruption of a thick series of platy pyroxene andesites, here termed the Juniper lavas, which extend westward from Juniper Lake for a distance of some four miles. Possibly these flows issued from vents that lie concealed beneath later ejecta in the region lying to the east of the Park. At about the same time a series of black, porphyritic lavas—the Twin Lakes andesites—poured out from a number of vents on the Central Plateau, flooding an area of at least 30 square miles * * *. Petrographically, these Twin Lakes andesites are peculiar by reason of their content of quartz xenocrysts, a feature deserving especial mention in view of the fact that the lavas lie adjacent to the recently erupted quartz basalt of Cinder Cone * * *.
>
> "At some time following the extrusion of the Twin Lakes andesites, vents opened in the vicinity of White Mountain [northwestern corner of the Mount Harkness quadrangle] and pyroxene andesite flows poured from it, chiefly to the south and east, extending for some five miles as far as the head of Warner Valley. To these flows the name Flatiron andesites has been applied. By this time the whole eastern portion of the Park seems to have been transformed into a relatively flat lava plain, conspicuously devoid of pyroclastic accumulations.
>
> "The next event was a renewal of activity immediately to the east of the Park, whereby thick flows of pyroxene basalt—the Eastern basalts—were poured out onto the Juniper andesites. Subsequent erosion of these basalts, which may not have extended much farther west than at present, produced the rugged hills that limit the Park on the east. Toward the close of this phase of activity there were many important pyroclastic eruptions, and possibly about the same time—the exact chronology is open to doubt—andesitic and basaltic cones were active along the northern boundary of the Park, in the vicinity of Badger and Table Mountains.
>
> "Meanwhile an enormous volcano had gradually been rising in the southwest corner of the Park, ultimately attaining a height of about 11,000 feet and a diameter of perhaps 15 miles. For this volcano the name Brokeoff Cone has been adopted. [This term is equivalent to the name "Tehama Volcano" used by other writers.] There is no means of telling when the cone commenced activity, but not improbably it was in existence when the Willow Lake basalts were being erupted. However that may be, most if not all of its exposed flows appear to be later than the Flatiron lavas. In a general way it may be said that the earliest of the Brokeoff lavas are augite andesites, above which follow hypersthene andesites interbedded, toward the top of the cone, with much tuff and breccia. The principal vent of this great volcano lay in the neighborhood of Supan's (Tophet) Springs [now Sulphur Works].
>
> "At some period during the later history of the Brokeoff cone, fluid lavas were being erupted from four shield volcanoes of Hawaiian type, situated one at each corner of the Central Plateau, namely Raker and Prospect peaks, Red Mountain, and Mount Harkness. By that time the Juniper and Flatiron andesites had been deeply denuded so that the new lavas poured over an uneven surface, many of them spilling down the sides of large valleys. Excepting Raker Peak, which is composed of pyroxene andesite, each of these broad, low cones or "shields" consists of pyroxene basalt, and all four are surmounted by well preserved cinder cones that rise within central, summit craters.
>
> "The eruptions of Red Mountain had entirely ceased when an irregular body of rhyolite was intruded into the cone at its northern base; likewise the Raker Peak volcano had long been dormant when a steep-sided, endogenous dome of hornblende-mica dacite was protruded through its southern flank * * *

Photo 3. Lossen crater on June 2, 1914. *Photo by B. F. Loomis.*

Photo 4. Lossen crater, eruption of September 29, 1914. *Photo by B. F. Loomis.*

Photo 5. Lassen Peak June 11, 1915. *Photo by B. F. Loomis.*

Photo 6. Volcanic bomb from Lassen Peak eruption, 1915. *Photo by B. F. Loomis.*

Photo 7. Lassen "mud flow" May 24, 1915. *Photo by B. F. Loomis.*

"Approximately at this time a new vent opened on the northeast slope of the Brokeoff cone, probably close to, if not immediately beneath the [present] edifice of Lassen Peak. As far as can be judged from the meager evidence this event was unheralded by strong pyroclastic explosions. From this new crater streams of fluid dacite flowed radially, but chiefly toward the north, piling up lava to a thickness of 1,500 feet. These are the black, glassy, beautifully columnar lavas that now encircle Lassen Peak, here referred to as the pre-Lassen dacites. If they are studied from the base upward, it will be found that their content of basic inclusions increases more or less regularly until in the topmost dacites of Loomis Peak [2 miles west of Lassen Peak] the inclusions may constitute as much as half the total volume. Mention is here made of this phenomenon because the dacite of Lassen Peak itself is likewise heavily charged with similar basic inclusions. Without doubt the large, almost structureless mass of Lassen represents a crater filling or plug-dome of Peléan type. The fluid, gas-rich magma has escaped from the crater to form the pre-Lassen flows; subsequently the gas-poor dacite, carrying with it abundant fragments from the hornblendic, basic crust of the magma reservoir, welled up sluggishly to build Lassen Peak. As the lava rose, partly solid and partly viscous, the margins of the dome were abraded and polished against the walls of the vent and the surface of the growing pile crumbled continually so as to construct enormous banks of talus.

"Smaller domes of viscous dacite rose to the south of Lassen Peak—at Bumpass Mountain, Mount Helen, Eagle Peak, and Vulcan's Castle—and some were connected with short, stumpy flows. Perhaps at this time also the dacite domes of Morgan and Boy Scout Hills were protruded through the southern base of the Brokeoff Volcano, and the dome of White Mountain was upheaved through the vents from which the Flatiron andesites had long before been erupted. Perhaps the domes that border Lost Creek also originated at this time. All these domes must have risen with great rapidity compared with the rate of growth of the earlier strato-volcanoes.

"Whether or not the emission of so much dacite was the immediate cause cannot be determined, but for some reason this phase of activity was succeeded by the collapse of the summit of the Brokeoff cone along a series of more or less vertical faults, thereby producing a vast caldera, approximately 2½ square miles in extent. In its mode of origin this caldera therefore simulates that of Crater Lake, Oregon. Many of the principal hot springs of the Lassen region are to be found within this faulted caldera of the Brokeoff cone.

"Lassen Peak had probably risen to its present height when a parasitic vent, Crescent Crater, erupted flows of dacite from its northeast flank. Then, about 200 years ago, a line of dacite cones developed at the northwest base of Lassen, from which showers of tuff and pumice were exploded. Two more or less cylindrical bodies of viscous dacite, each about a mile in diameter, were subsequently protruded through these cones and now form the Chaos Crags. Hardly had the later, northern dome of dacite been emplaced, having risen some 1,800 feet, than steam explosions issued from its northern base, causing that whole side of the mass to collapse and precipitating a great avalanche of angular blocks which lie strewn over an area of 2½ square miles, a wilderness of debris known as the Chaos Jumbles * * *

"The complicated history of Cinder Cone, in the northeast part of the Park, commenced with violent pyroclastic explosions, producing not merely the cone itself but mantling an area of more than 30 square miles with a sheet of fine ejecta. Possibly this occurred about 500 A.D. Subsequently blocky flows of quartz basalt were erupted and after these had been partly concealed by the products of further explosions, there were at least two

Photo 8. Lassen Peak eruption, 1915. *Photo courtesy of Oakland Tribune.*

Photo 9. Cinder Cone, Lassen Volcanic National Park. This area was in eruption in the 1850s. *Photo by Mary Hill.*

Photo 10. Chaos Crags, Chaos Jumbles. *Photo by Robert Stinnett, courtesy of Oakland Tribune.*

Photo 11. Manzanita Lake and Lassen Peak. *Photo by Mary Hill.*

Photo 12. Lassen Peak. *Photo by Mary Hill.*

> more eruptions of blocky lava, the latest of which is reliably dated as occurring in 1851.
>
> "Steam was seen to be rising from the domes of the Chaos Crags as late as 1857, but no further important eruptions took place in this region until May, 1914, when Lassen itself burst into activity. For a year explosions recurred at irregular intervals. In May, 1915, a mass of lava rose into the summit crater, spilling over the rim on the northwest and northeast sides and causing extensive mud flows by the melting of the snows. On May 22, a horizontal blast issued from the northeast side of the crater, resulting in further damage along the headwaters of Hot and Lost creeks. Thereafter activity declined, finally ending in the summer of 1917. Since that date the volcano has lain dormant."

Heath (1960) has shown that the Chaos Jumbles were produced by several, probably three, separate avalanches. His date of approximately 1700 A.D. for the formation of the last portion of the Jumbles, based on tree-ring counts and an estimate of the time required for establishment of vegetation on the deposit, is a good confirmation of Williams' earlier estimate of approximately 200 years for the age of the deposit.

Another event late in the history of the volcano was a glowing avalanche that swept down the valley of Manzanita Creek, northwest of Lassen Peak, depositing an unsorted mass of pale-gray to white dacite blocks and weakly breadcrusted pumice bombs in a matrix of dacite ash (Macdonald, 1963). The deposit can be seen at the Sunset Campground, west of Manzanita Lake, and a small remnant crosses the highway just outside the Manzanita Lake entrance to the National Park, where it rests on the Chaos Jumbles. Charcoal fragments from the deposit close to the campground yield a $C^{14}$ age of less than 200 years (Rubin and Alexander, 1960, p. 156). The avalanche appears to have come from Lassen Peak but may have occurred at about the time of the last eruption of the Chaos Crags.

Brief mention should also be made of the pumice ejected during the 1915 eruption of Lassen Peak. The pumice is conspicuously banded, with light streaks of dacite and dark ones of andesite. The bands appear to represent two distinct magmas, imperfectly mixed at the time of eruption (Macdonald and Katsura, 1965). Many blocks of this banded pumice can be found in the vicinity of the Devastated Area parking lot, near the eastern base of Lassen Peak.

Several groups of hot springs and fumaroles exist in and near Lassen Volcanic National Park. Supan's Springs, at the Sulphur Works, on Highway 89 near the south entrance of the park, issue from andesite flows and breccias of the Brokeoff Volcano within the caldera, as also do others along Mill Creek and its tributaries, Sulphur Creek and Little Hot Springs Valley. The springs and fumaroles of Bumpass Hell occupy a basin between the dacite dome of Bumpass Mountain and the andesites of Brokeoff Mountain. Most of the springs contain small amounts (19 to 436 mg/1) of sulfuric acid, derived from the oxidation of $H_2S$ in rising magmatic gases, either directly, or by oxidation of native sulfur that is in turn derived from $H_2S$ (Day and Allen, 1925, p. 113, 138). In each spring area the highest temperature of the water generally is close to the boiling temperature at the altitude of the particular spring or fumarole—91° to 92°C at Bumpass Hell and Supan's Springs—but fumarole temperatures as high as 117.5°C have been observed. Depending largely on the abundance of the water supply, the springs vary from clear pulsating springs to mud pots, the spattering of the latter sometimes building enclosing cones to form mud volcanoes. There are no true geysers. The rocks around the springs are altered, ultimately largely to opal and kaolin, accompanied by minor amounts of alunite (Anderson, 1935). The structures and textures of the original rocks are often almost perfectly preserved in the opalized residuals. Where acidity is comparatively high, nearly pure opal is formed, but where it is lower, kaolin is the principal product. In addition to opal, kaolin, and alunite, the sediments in the springs and along their drainage channels contain sulfur, pyrite, tridymite, and quartz. The two latter minerals may be in part residual from the original rocks but appear to have been formed partly within the hot springs.

The area of solfataric alteration within the Brokeoff caldera is approximately 5 square miles and is much more extensive than the present hot-spring basins (Williams, 1932a, p. 259). Solfataric and hot-spring activity seems to have been at one time much more widespread than it now is.

Studies by R. W. Bowers and L. C. Pakiser over an area of 4,000 square miles in the southern Cascade Range and adjoining Modoc Plateau have demonstrated an area of negative gravity anomaly that is centered in the Lassen region and extends southeastward into the Lake Almanor basin (Pakiser, 1964). The gravity low, which covers an area of about 2,000 square miles, has a maximum amplitude of 70 mgals and a steep gradient of 8 mgals per mile on the western side. Pakiser finds that it can be explained by a volume of about 15,000 $km^3$ of light material in the outer part of the earth's crust, with a density contrast between it and the enclosing rocks of 0.2 grams per $cm^3$. Possible explanations of the low-density mass include: (1) a batholith of silicic rock beneath the volcanic rocks; (2) a thick accumulation of sedimentary rocks beneath the volcanic rocks, deposited in the Lassen Strait; (3) a low-density mass caused by thermal expansion of crustal rocks resulting from volcanic heat; (4) a volcano-tectonic depression filled with light volcanic rock. All four may contribute to the deficiency of gravity in the area. Certainly, heating of adjacent rocks must have occurred during the rise of magma through the volcanic conduits, and Pakiser (1964, p. 618) considers that this may explain the local gravity lows observed in the vicinity of some of the volcanoes, such as Lassen and West Prospect Peaks. Also, petrographic evidence suggests the fusion of crustal material to supply some of the erupted lavas (Macdonald and Katsura, 1965, p. 479–480), which may have resulted in the formation of a low-density batholithic mass beneath the area. Partly because of the steep gravity gradient on the western edge of the region, the fourth explanation appears the most likely for the major part of the anomaly (Pakiser, 1964, p. 618). Pakiser makes the reasonable suggestion that the sunken region was the source of the Nomlaki Tuff and that large volumes of low-density ash and other volcanic material were deposited in the subsiding structure. Similar deficiencies of gravity are found at many collapse calderas and volcano-tectonic depressions in continental regions.

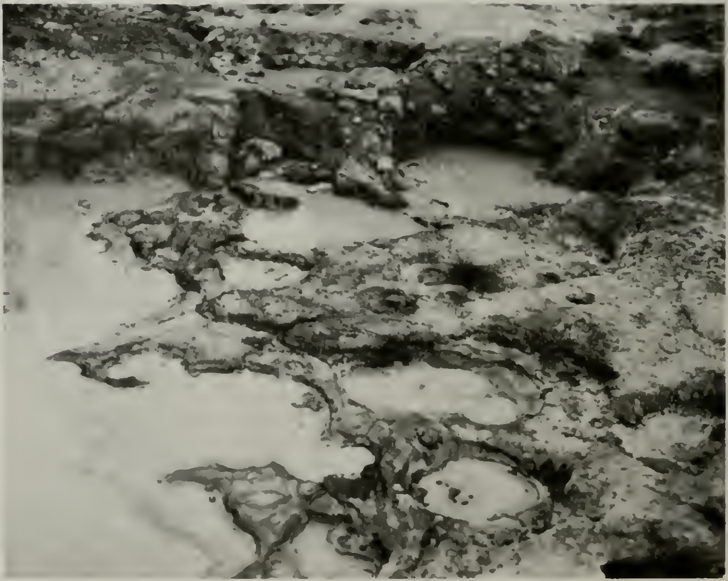
*Medicine Lake Highland.*—The Medicine Lake area (Medicine Lake and adjacent quadrangles) has been studied by C. A. Anderson, and the following brief account is abstracted from his report (1941).

The oldest rocks in the region are a series of fragmental deposits of basaltic and andesitic composition, correlated by Powers (1932, p. 259) with the Cedarville Series in the Warner Mountains, 60 miles to the east. Similar rocks are widespread in the Modoc region north, east, and south of Medicine Lake. They have been block faulted, and the lower parts of the fault blocks buried by the widespread "plateau" basalts referred to by both Powers and Anderson as the Warner Basalt. Both the Cedarville Series and the Warner Basalt will be discussed in the section on the Modoc Plateau; it will suffice here to say that they appear to be the basement on which the rocks of the Medicine Lake Highland accumulated.

Northwest of the Highland, the Warner Basalt is covered by a sheet of massive andesite tuff. Near Dock Well, 7 miles northwest of Medicine Lake, the tuff is more than 200 feet thick, with no visible stratification. It ranges from gray to pink or buff in color, and contains pumice fragments commonly up to an inch across, in places up to 3 inches across, in a fine

Photo 13. Bumpass Hell, Lassen Volcanic National Park. *Photo by Mary Hill.*

Photo 14. Devils Kitchen, Lassen Volcanic National Park. *Photo by Mary Hill.*



silty matrix. Some of the pumice lapilli are flattened and stretched, and the glass is partly devitrified. In places the tuff is slightly welded (Anderson, 1941, p. 356). There appears to be little question that it is the product of a glowing avalanche (pumice and ash flow). Its source is unknown, but probably it is genetically related to flows and domes of platy rhyolite and rhyolite obsidian that crop out at nine places around the base of the Medicine Lake volcano. These obsidians are locally spherulitic, and in the mass between Cougar Butte and the road from Lava Beds National Monument to Tionesta (Timber Mountain quadrangle), lines of spherulites give it a pronounced parallel structure. At the same locality, lithophysae are lined with cristobalite and small black tablets of fayalite (Anderson, 1941, p. 356). At one place on the north slope of the Highland, a small mass of stony dacite overlies the obsidian. The distribution of the rhyolites indicates that they are related to a volcanic center beneath the present Highland.

West of Medicine Lake Highland, a group of cones, as much as 1,000 feet high, are built of very massive basalt containing conspicuous phenocrysts of white plagioclase and reddish-brown altered olivine. Some of the lava flows must have been quite viscous, since the north side of the cone a mile northwest of Pumice Stone Mountain consists of a series of superimposed flows, each ending in a steep front, giving the slope a terraced aspect (Anderson, 1941, p. 357). The massive basalts are probably of about the same age as the rhyolites mentioned in the last paragraph.

The growth of the present Highland began with the eruption of rather fluid pyroxene andesites, which gradually built up a broad shield volcano some 20 miles across, with a slope of only about 3°. No intercalated pyroclastic material is found. The flows consist of a dark-gray vesicular surface portion, 3 to 6 feet thick, terminating sharply against an interior medium to light-gray dense portion characterized by conspicuous platy jointing. The earliest lavas contain 2 or 3 percent of small phenocrysts of yellowish olivine, whereas the later ones are generally olivine free. The platy andesites overlie the massive basalts, the andesite tuff, and the rhyolites. They are best exposed on the northwest side of the Highland, but most of the shield has been buried beneath later volcanics.

The ultimate height of the shield was probably about 2,500 feet, but Anderson (1941, p. 352, 359–362) concludes that after the growth of the shield its summit collapsed to form a caldera 6 miles long and 4 miles wide, with its rim some 500 feet below the level of the former summit. Lava then rose along the arcuate marginal fractures, poured as flows into the caldera, and built cones that eventually surmounted the caldera rim and allowed some of the later flows to pour down the outer slope of the shield. The result was a series of eight separate rim volcanoes around the caldera which have completely hidden the former caldera boundaries. The present lake basin is the depression left between these rim cones.

The earliest postcaldera lavas were platy olivine-free andesites, resembling the last precaldera lavas. Later these gave way to olivine andesites, dacites, and rhyolites. The eruptions of platy andesite built ridges around the north, west, and south of the basin, the northern one capped by four cinder cones. A small mass of perlitic rhyolite is associated with the andesite in the western ridge. Presumably a similar, but somewhat lower, ridge was built on the east side of the basin, since its lavas are exposed northwest of Mount Hoffmann, but it is largely hidden by later volcanics of three separate complexes: Red Shale Butte, and Lyons Peak, both about 5 miles east of Medicine Lake, and Mount Hoffmann, 2 miles east of Medicine Lake. Volcanic activity in the Red Shale Butte complex started with eruption of platy olivine andesites resembling the early lavas of the underlying shield. These were followed by the Lake basalt of Powers (1932) —a flow of coarsely porphyritic olivine basalt that poured into the central basin and now forms the eastern and northeastern margins of Medicine Lake. The Lake basalt contains numerous phenocrysts of white plagioclase along with those of yellow-green olivine. It was followed by platy andesites, resembling those in the ridges north and south of the basin that built Red Shale Butte and Lyons Peak. In the latter complex, some of the lavas are dacitic and contain large amounts of brownish glass. In contrast, the Mount Hoffmann complex consists largely of silicic lavas, predominantly rhyolites, with basalt flows at the base:

> "The Mount Hoffmann complex is essentially a circular table built up by successive outpourings of very viscous perlitic rhyolite, each flow ranging from 50 to 150 feet in thickness * * *. The closing stages of activity at the summit were marked by the eruption of a short eastern tongue of perlitic rhyolite, about 100 feet in thickness, followed by the protrusion of a dome about 200 feet high above the short flow. The two, combined, form a topographic dome some 300 feet above the circular table. (Anderson, 1941 p. 356.)
>
> "The picture during the late Pleistocene was undoubtedly that of a northern ridge of platy andesite passing into the circular table of Mount Hoffmann perlitic rhyolite, separated by an ice cap from the Red Shale Butte complex of basalt and platy andesites, which in turn was separated from the Medicine Mountain platy andesites by a second ice cap. A third covering of ice occupied the broad ridge of platy andesites west of the summit basin * * *. As the ice disappeared, Medicine Lake came into existence, filling the summit basin. Continued volcanic activity produced cones and lava flows, and most of the later products show weak or no glaciated surfaces and for that reason have been related to the Recent * * *." (Anderson, 1941, p. 367.)

More than 100 basaltic cinder cones, ranging in age from late Pleistocene to Recent, are present in the 400-square-mile area of Anderson's map. They are scattered over the entire Highland, on the floor and rim of the summit basin as well as on the outer slopes of the old shield, and on the surrounding plateau. The cones in the summit basin and on the rim "stand alone" (Anderson, 1941, p. 368), but most of the others are accompanied by lava flows. Great floods of basaltic lava were poured from vents on the north, east, and south flanks of the Highland. These were termed the Modoc Basalt by Powers (1932, p. 272). They include the flows of the Lava Beds National Monument.

> "In many places the Modoc basalt flows emerged from fissures bearing no relationship to cinder cones. One of the most striking examples is on the road north of High Hole Crater [on the southeast flank of the Highland], where a fissure supplied part of the lava for the Burnt Lava flow. [The rest of the flow came from High Hole Crater.] Another good example can be seen * * * east of Lava Camp (on the northern flank of the Highland), where three fissures discharged basalt to the northern lava field." (Anderson, 1941, p. 368.)

Flows of the Modoc Basalt include nearly aphyric rocks, containing only a few small phenocrysts of olivine and an intersertal texture that may be seen with the hand lens, and porphyritic rocks with conspicuous plagioclase phenocrysts in a dark-gray aphanitic, microcrystalline, hyalo-ophitic to hyalopilitic, rarely intergranular or intersertal, groundmass. The basalts of the latter type grade into andesites. Flows of the first type include both pahoehoe and aa, with pahoehoe predominant. The flows of the second type are nearly all aa, grading into block lava, and are commonly younger than those of the first type. The flows of the Lava Beds National Monument will be discussed in the next section.

Three very recent basaltic lava flows on the flanks of the Medicine Lake Highland are singled out for special mention. All three are largely aa, but locally have pahoehoe and block-lava surfaces. Possibly the oldest of the three is the flow called the Callahan flow by Peacock (1931, p. 269). It covers about 10 square miles on the lower northern slope of the Highland. The Paint Pot Crater flow (Anderson, 1941, p. 371), just southwest of Little Glass Mountain on the southwest flank of the Highland, has an area of only about 1 square mile. Its source, Paint Pot Crater, is a basalt cinder cone mantled with a thick layer of white pumice from the eruption of Little Glass Mountain. Pumice Stone Mountain, just to the north, is an older basaltic cinder cone similarly covered by pumice. Most picturesque and youngest in appearance is the Burnt Lava flow (Peacock, 1931, p. 269–270) on the southern flank of the Highland, easily accessible by the road that leads southeastward from Medicine Lake. The lava issued from the vent marked by the cinder cone of High Hole Crater and from a fissure just to the north. The lava field covers an area of about 14 square miles, but consists of at least two flows of different age (Finch, 1933): The older is a highly oxidized aa exposed near the south end of the field, and the younger consists of pahoehoe partly overridden by aa which has buried a large part of the older flow. The lava is basaltic in appearance, but chemically it is a basaltic andesite, with a silica content of more than 55 percent and a color index of less than 30. The same is true of many other flows in the Modoc Basalt and other young basaltic flows of the Modoc Plateau.

Very late in the history of the Medicine Lake Highland came a series of silicic eruptions. These include: A black, glassy to stony flow of dacite poured out on the floor of the summit basin just north of Medicine Lake, where it covers about 1 square mile; another dacite flow in the gap between Mount Hoffmann and Red Shale Butte; another slightly older one east of Glass Mountain; a flow of perlitic rhyolite on the northeast flank of Mount Hoffmann; a small mass of rhyolite obsidian on the northwest rim of the summit basin; and the two striking masses of rhyolite obsidian that form Glass Mountain and Little Glass Mountain. The Little Glass Mountain eruption began with explosions that showered pumice over the surrounding country. Fragments of pumice can be found as far away as 15 miles to the southwest. Probably a cone of pumice was built around the vent, but it was either destroyed or wholly buried by the ensuing flows. Two separate flows were extruded, the second completely burying the first except at the northeast corner. An excellent view of them can be had from the summit of Little Mount Hoffmann, which is accessible by car. The flow is roughly rectangular and averages a little more than 1½ miles across. Its margins are 50 to nearly 200 feet high, and it is probably more than 500 feet thick in the middle. Its volume probably exceeds 0.1 cubic mile.

The history of Glass Mountain is more complex (Anderson, 1933b; Chesterman, 1955). The first event was the opening of a fissure trending N. 30° W., along which explosions built at least seven cones of pumice, the largest at the site of the present Glass Mountain. The surrounding area, particularly to the northeast, was showered with pumice. Ten miles from the vents the pumice layer is several inches thick, and near Glass Mountain it is as much as 60 feet thick, with pumice blocks up to 2 feet in diameter. At the other cones, finely vesicular glass rose in the vents, forming domes, most of which breached the cone walls and flowed a short distance beyond. At Glass Mountain a much larger flow issued, pouring mostly eastward to form a flow 3½ miles long which was split into two tongues by the slightly older mass of dacite mentioned above. The eastern tongues are of stony dacite containing numerous inclusions of olivine basalt. The dacite passes abruptly into rhyolitic obsidian through a transition zone in which both rock types are present, the main part of the flow consisting of rhyolitic obsidian devoid of basaltic inclusions (Anderson, 1941, p. 375–376). At the end of the eruption, the lava was so viscous that it was pushed up into a small dome. Renewed activity resulted in a second, smaller flow that partly covered the first. Both obsidian flows have pumiceous to scoriaceous surface phases and dense glassy interiors. The final stage of activity consisted in the rise of a dome of microvesicular rhyolitic glass, a quarter of a mile in diameter and 150 feet high, whose summit bristles with partly collapsed spines.

Photo 15. Little Glass Mountain and Mount Shasta from Little Mount Hoffman. *Photo by Mary Hill.*

North of Glass Mountain two beds of pumice are separated by 6 to 12 inches of soil, showing that the eruptions were interrupted by a considerable period of quiescence. The upper pumice ranges in thickness from a few feet to 30 feet, and contains upright trunks of ponderosa pines that were rooted in the soil layer on the lower pumice (Chesterman, 1955). Growth rings indicate that the largest trees were at least 225 years old at the time they were killed by the upper pumice fall; the interval between the two pumice falls —making allowance for the time required to establish plant growth—is estimated by Chesterman to have been around 300 to 350 years. Radiocarbon age determinations made by W. F. Libby on the tree trunks, give a maximum of 1,660 ± 300 years and a minimum of 1,107 ± 380 years, with an average of 1,360 ± 240 years (Chesterman, 1955). The upper pumice thus has a probable age of about 1,400 years and the lower about 1,700 years.

Was the Glass Mountain obsidian flow the last eruptive activity in the Medicine Lake region? All of the young basalt flows mentioned above have bits of pumice and rhyolitic obsidian scattered over their surfaces, and the Callahan and Paint Pot Crater flows are almost unquestionably older than the last silicic eruptions. On the more recent part of the Burnt Lava flow, however, the pumice is very small in amount, and has probably been blown onto the lava by the wind. The flow is close to Glass Mountain, and if it had been present at the time of the eruption that produced the last thick fall of Glass Mountain pumice, the amount of pumice on the flow would be much greater. Adjacent older lavas and islands within the flow have much more pumice on their surfaces, and the pumice can hardly have been removed from the exceedingly rough surface of the Burnt Lava flow by running water. The largest trees growing on the older part of the Burnt Lava flow have been estimated to be only 300 years old, and the surface of the younger part is so fresh in appearance that Finch (1933) considered that it could easily be less than 300 years old. Charcoal samples from a tree stump buried by the flow give an age of only 200 ± 200 years (Ives and others, 1964, p. 49). It appears probable that at least the younger part of the Burnt Lava flow is more recent than the big eruption of Glass Mountain. The same conclusion has been arrived at independently by C. W. Chesterman (written communication, 1965).

Even this may not have been the last eruption! Finch (1928) cites a report of a light ash fall that coated leaves of plants in the nearby area in 1910 and suggests that the ash may have come from a small explosive eruption of Glass Mountain.

*Lava Beds National Monument.*—Although the area of the Lava Beds National Monument is geologically most closely related to the Modoc Plateau, the area is located immediately north of the Medicine Lake Highland, and it is convenient to discuss the two contiguously. The rocks of the Monument are the Modoc Basalt of Recent age. Most of the surface is covered with pahoehoe flows containing numerous lava tubes, some of which served as shelters for Captain Jack and

Photo 16. Schonchin Butte, Modoc Lava Beds. *Photo by Mary Hill.*

his band of Modoc Indians during the Modoc War of 1872–73. Of the 300 lava tubes known within the Monument, about 130 have been explored; they range from a few feet to about 75 feet in diameter. Some have two or three levels, separated by nearly horizontal septa formed by the freezing of the surface of the lava stream in the tube during a pause in the lowering of the surface of the stream toward the end of the eruption. In the lower levels of some caves percolating water freezes during the winter to form ice that persists, only partly melted, through the next summer. Lava stalactites are common on the roofs of the caves, and occasional stalagmites are found on the floors. Quite commonly, an increase in the viscosity of the last fluid lava moving through the tube has resulted in a change of the lava to aa and the formation of a layer of aa clinker on the floor of the pahoehoe tube. The roofs of some tunnels have collapsed to form long winding trenches, 20 to 50 feet deep and 50 to 100 feet wide (Stearns, 1928), with occasional short uncollapsed sections forming natural arches. Tumuli (pressure domes) are present on the pahoehoe flow surfaces, and ropy surface is preserved in places, but most of the surfaces are smooth or billowy.

Less abundant than pahoehoes are flows of aa, such as the Devils Homestead flow, that is visible from the highway 6 miles north of the Monument Headquarters. Others include the flow from Schonchin Butte,

Photo 17. Lava flows from Schonchin Butte. *Photo by Mary Hill.*

a small flow from Black Crater 2 miles to the northwest, and in the southwestern corner of the Monument part of the Callahan flow (known also as the Black Lava flow).

About a dozen cinder cones, 50 to 700 feet high, lie within the Monument, and were formed by moderately explosive Strombolian-type eruptions at the vents of some of the flows. Perhaps the best example is Schonchin Butte, just east of the highway 2 miles northwest of Monument headquarters. Elsewhere, the eruptions were less explosive and built spatter cones, commonly in lines along fissure vents. A good example of these is the Fleener Chimneys, 0.8 miles west of the highway on a branch road 2 miles northwest of Schonchin Butte—a row of spatter cones built by Hawaiian-type eruption at the vents of the Devils Homestead lava flow. Some other spatter and driblet cones are rootless hornitos, built by escape of gas-charged lava through holes in the roofs of underlying lava tubes. Mammoth Crater, on the road to Medicine Lake at the south border of the Monument, was formed by the collapse of the summit of a lava-armored cinder cone as a result of lava draining from the underlying conduit through a tube in the cone wall.

Prisoners Rock, at the Petroglyph Section, a few miles northeast of the main part of the Monument, is a remnant of a cone of palagonite tuff, dissected by sub-aerial erosion and cliffed by the waves of ancient Tule Lake. Just north of it lies another similar cone. These cones resemble Diamond Head and Punchbowl, in Honolulu, and Fort Rock and nearby cones in central Oregon, and like them were formed by phreatomagmatic explosions where rising basaltic magma encountered water. The cones appear to be older than most or all of the lava flows in the main part of the Monument.

Some of the flows in the Monument, particularly the Devils Homestead flow, appear to be very recent. However, all of them have bits of silicic pumice scattered over their surfaces and are probably older than the last silicic eruptions in the adjoining Medicine Lake area. By comparison with flows in other regions, Stearns (1928, p. 253) estimated that none of them are younger than 5,000 years.

At the northwest edge of the Monument, Gillem Bluff is an excellent example of one of the recent fault scarps that are widely distributed over the Modoc Plateau. It is one of three east-facing scarps that form the western side of the Tule Lake basin.

## MODOC PLATEAU

The Modoc region consists of a series of northwest- to north-trending block-faulted ranges, with the intervening basins filled with broad-spreading "plateau" basalt flows, or with small shield volcanoes, steeper sided lava or composite cones, cinder cones, and lake deposits resulting from disruption of the drainage by faulting or volcanism. The oldest rocks are of Miocene, or possibly of Oligocene age, and the youngest are Recent. Although the faulting culminated in late Miocene or Pliocene, it has continued into Recent time. The Modoc region is best regarded as a part of the Great Basin province that has been flooded by volcanics, which are perhaps related to the Cascade volcanic province.

### Cedarville Series

Petrographically, the Warner Range, which adjoins the Modoc Plateau on the east, is a part of the Modoc Plateau province. The oldest rocks recognized in the Warner Range constitute the Cedarville Series of Russell (1928, p. 402–416), divided by him into lower and upper units consisting largely of andesitic fragmental beds, separated by a middle lava member. The lower and upper units consist mainly of tuffs, tuff-breccias and agglomerates, ignimbrites, and mudflow deposits, with a subordinate amount of intercalated andesite lava flows. The lower unit contains an abundant middle Oligocene flora and a rhinoceros jaw of probable early Miocene age (Gay, 1959, p. 6), and the upper member is of late Miocene age (LaMotte, 1936).

The oldest rocks in the Modoc region are exposed only in the relatively uplifted fault blocks and have been tilted, commonly between 20° and 30°. Because of similarity in lithology and structural relationships, Powers (1932, p. 258–259) correlated them with the type Cedarville Series of the Warner Range, but

Photo 18. Interior of lava tube, Modoc Lava Beds. *Photo by Mary Hill.*

pointed out that in general there is no indication whether the rocks of the Modoc Plateau are equivalent to the lower or upper unit of the Cedarville, or to both. A middle Miocene flora is present in lake sediments intercalated with the volcanics in the mountains between Canby and Adin (Gay, 1959, p. 6).

Little can be added to Powers' (1932, p. 258–259) description of the Cedarville Series of the Modoc region:

> "The oldest series of volcanic rocks of the area was recognized in the field by the abundance of pyroclastic material, tilted and warped structure, and the gentle slopes eroded on its non-resistant pyroclastic members. The series shows great range in lithology: basaltic flows, intrusives, and pyroclastics; andesitic flows and pyroclastics; and rhyolitic intrusives and pyroclastics * * *. The basalt is typically dark gray to black and has a fine-grained, compact texture. Most of the specimens collected have the ophitic or intersertal texture common to the typical plateau basalt * * *. They are notable for the presence of chlorophaeite which is not found in the younger basalts of the area * * *. A few of the basalts show an intergranular texture * * *.
>
> "Andesitic members are most abundant in the series, and of these the pyroclastic rocks predominate. The lava specimens collected are all pyroxene andesites with both hypersthene and augite as phenacrysts. Fragments of hornblende andesite are found in detrital material.
>
> "Rhyolites are represented chiefly by beds of pumice-tuff. Fragments of pumice three to four inches in diameter are included in a matrix of smaller fragments of the same material. One dike of compact, reddish felsite was found which shows a brecciated border zone cemented by colorless to white opal."

Some of the fragmental beds are the tops and bottoms of block-lava flows, and others are mudflow deposits, rather than "pyroclastic" rocks in the sense of being direct deposits from explosive activity. Blocky flow tops and bottoms are well exposed in cuts on Highway 299 half a mile east of the Pit No. 1 Powerhouse, interbedded with massive to platy central portions of the flows. Irregular tongues of the massive lava intrude the breccias. Near the top of the same highway grade, a segment of a red cinder cone is interbedded with the lava flows. Mudflows of the Cedarville Series are well exposed in cuts along Highway 299, 8 miles northeast of Alturas.

Rhyolite and rhyolite obsidian in the region near Hambone, and at various places within the area of the Warner Basalt farther northeast, may belong to the Cedarville Series.

At Hayden Hill, 15 miles south-southeast of Adin, gold was formerly mined from an epithermal deposit in silicified rhyolite tuff. Gold-bearing veins are also present in andesitic volcanic rocks in the Winters district, southwest of Alturas, and in rhyolitic rocks in the High Grade district, northeast of Alturas (Clark, 1957, p. 219).

Sedimentary rocks are intercalated with volcanic rocks of the Cedarville in some areas. Along Highway 299, where it climbs the western flank of the Big Valley Mountains at the east side of Fall River Valley, rhyolitic tuff and tuffaceous sandstone, as well as mudflow breccias, are exposed. Miocene lake beds, including diatomite, crop out farther north in the same range, in the mountains to the northeast, at some other localities in that area (Gay, 1959, p. 5), and in the vicinity of the Madeline Plains 45 miles southeast of Alturas.

The Cedarville is probably equivalent in age to predominantly volcanic formations, such as the Ingalls, Delleker, and Bonta Formations of Durrell (1959), in the northern Sierra Nevada and adjacent parts of the Great Basin.

### Pliocene Rocks Other Than Warner Basalt

About the end of the Miocene Epoch, the Modoc Plateau region was shattered by tectonic movements, and rocks of the Cedarville Series were broken, tilted, and elevated into a series of mountain ranges by faulting. The drainage system was disrupted, and in the basins between the ranges, a series of fresh-water lakes were formed in which sediments accumulated. Volcanism continued, and lava flows, subaerial and water-laid ash beds, mudflow deposits, and the deposits of incandescent ash flows (ignimbrites) were mingled with the sediments. In some places the accumulations were wholly sedimentary, elsewhere volcanic layers were intercalated with the sedimentary rocks, and in still other places the sequence is nearly or entirely volcanic. The lava flows are predominantly mafic, being basalts and basaltic andesites; the pyroclastic rocks are predominantly rhyolitic.

Pliocene lake beds are exposed along the valley of the Pit River for more than 20 miles west of Alturas, for an equal distance southward along the South Fork of the Pit River, and for 10 miles northeastward along the North Fork. These have been called the Alturas Formation by Dorf (1930, p. 6, 23). They include diatomite, diatomaceous and tuffaceous silty and sandy shale, siltstone, and sandstone. Locally, strongly current-bedded sandstone and conglomerate are probably of fluviatile, rather than lacustrine, origin. The lake beds contain a middle Pliocene flora and Pliocene mammalian remains (Gay, 1959, p. 6). Interbedded with the sediments southwest of Alturas are layers of ignimbrite containing many lumps of pumice. They can be seen along Highway 299, 8 to 10 miles west of Alturas, and in the plateau escarpment to the north. South of the highway a layer of welded ignimbrite locally forms the resistant caprock of the Alturas Formation, where less resistant overlying lake beds have been eroded away. A second, slightly less welded layer lies a few feet lower in the section. The rock has been quarried for building stone, and the cut stone can be seen in the Elks Club building (the former railway station) in Alturas. Similar ignimbrites are associated with lava flows, mudflow deposits, and sediments in the mountains farther west, between Canby and Adin. In a bed well exposed in a highway cut 0.9 mile south of Adin Pass, some of the lumps of pumice are more than a foot long. In the same cut, mudflows of ignimbritic debris grade in their upper parts into poorly bedded material reworked by water.

Rattlesnake Butte, 10 miles west of Alturas, the type locality of the Alturas Formation (Dorf, 1930), marks the site of a volcanic vent. The sedimentary beds are steeply upturned around the central basaltic neck. The age of the vent may have been either late Pliocene or early Pleistocene.

According to G. W. Walker (oral communication, 1965), the uppermost beds that are generally included in the Alturas Formation north and west of Alturas are nearly horizontal and locally are separated by an angular unconformity from the lower part of the formation. The latter, which contains the beds of ignimbrite mentioned above, was faulted and gently folded, and was eroded before the deposition of the upper beds. In places, however, no unconformity can be found, and sedimentation was probably essentially continuous throughout the period of accumulation of the formation. The upper, horizontal beds contain upper Pliocene gastropods and Pliocene or Pleistocene mouse teeth (Gay, 1959, p. 6). Local deformation and erosion in some areas appears to have been concomitant with continued sedimentation in other nearby areas.

Diatomaceous lake beds are well exposed also around Lake Britton, 10 miles north of Burney, and along the valley of the Pit River for 5 miles east of the lake. They are well displayed where Highway 89 crosses the lake, and where Highway 299 crosses Hat Creek. Diatoms from these deposits have been studied by G. Dallas Hanna, who states that they are of middle and late Pliocene age. Similar sediments are found along the valley of Willow Creek, southwest of Lower Klamath Lake and northwest of the Medicine Lake Highland. Still farther northwest, near the village of Dorris, sandstones and conglomerates contain nonmarine gastropods of late Pliocene age (Hanna and Gester, 1963).

In most areas the lake beds were slightly tilted and eroded before they were overlain by the Warner Basalt (see next section). Along Highway 299, about 7 miles northeast of Alturas, white pumice-lapilli tuffs appear to belong to the Alturas Formation, although they are tilted at angles greater than 30°. They are closely similar to nearly horizontal lapilli tuffs in the Alturas Formation a few miles farther west. In the area northeast of Alturas they exhibit striking conical erosional forms, resembling haystacks or beehives, as much as 20 feet in basal diameter and 30 feet high.

In the southwestern part of the Modoc region, just north of Lassen Volcanic National Park, the uplifted fault blocks are composed of andesite lava flows identical with, and unquestionably correlative with, the post-Tuscan lavas of the adjacent Cascade Range. Farther eastward, in the Harvey Mountain and Little Valley quadrangles, similar fault blocks consist of basalt and olivine basalt. The very late Pliocene andesitic volcanism in the Cascade Range gave way eastward to basaltic volcanism. In both areas the bases of the fault blocks are submerged in the Burney (Warner) Basalt.

In the southeastern part of the Modoc Plateau region, many small shields of basalt and basaltic andesite, although considerably eroded, still retain their general constructional form. These appear to be certainly younger than the Pliocene rocks in the fault blocks, which have not only been much more disrupted by faulting but also have suffered much more erosion. They are nevertheless older than the widespread Warner Basalt and older than Pleistocene lake beds, and are regarded as of late Pliocene or Pliocene and Pleistocene age. As examples there may be mentioned Roop Mountain, 10 miles west-northwest of Susanville, and several mountains lying between Honey Lake and the Madeline Plains. Just north of Lake Britton, Soldier Mountain is one of this group, resting against the Cedarville Series of the Fort Mountain fault block.

### Warner Basalt

The plateau basalt that is widely distributed between the fault-block ranges of the Modoc region is commonly referred to as the Warner Basalt of Russell (1928). It was named in the Warner Mountains, where R. J. Russell found a sheet of basalt capping the Cedarville Series; but Russell (1928, p. 416) believed that the same basalt was the most widespread unit in the Modoc Lava-Bed quadrangle to the west. This was accepted by Powers (1932, p. 266) and Anderson (1941, p. 353), though both Fuller (1931, p. 115) and Anderson recognized that it might not be possible to group all of the "plateau" basalt of the area into a single stratigraphic unit. Actually, considerable variation in both the degree of weathering and the thickness of the ashy soil cover on the basalt at different places, as well as other differences in geological relationships, indicate that there is considerable difference in age of the basalt from one place to another, and it is preferable to use local formation names until the correlation of the basalts throughout the region can be more firmly established. The name Burney Basalt has been used in this way for the plateau basalt in the Prospect Peak and Harvey Mountain quadrangles (Macdonald, 1964, 1965) and in the Burney and Little Valley quadrangles just to the north, and the name Gardens Basalt has been used by Ford and others (1963) in the area just northwest of Alturas. For the purpose of this report, however, Russell's name Warner Basalt is herein retained as a collective term for the petrographically and structurally similar lavas throughout the region, without any specific implication as to contemporaneity.

In the Warner Mountains the Warner Basalt overlies the tilted upper Cedarville Series conformably, but throughout the rest of the region it rests against the eroded edges of fault blocks composed of tilted Cedarville and younger rocks. Since the upper Cedarville is of probable late Miocene age, the Warner Basalt in the Warner Range cannot be older than late Miocene, but the lack of any structural deformation between it and the underlying rocks suggests that there may not be any great difference in their ages. Both have been tilted westward with the uplift of the Warner Mountains fault block and the basalt appears to be overlain by Pliocene volcanic rocks and lake-bed deposits of the Alturas Formation. The latter is in turn deformed, eroded, and locally overlain by a later series of lake-bed deposits, which in turn is capped by a plateau basalt not older than latest Pliocene and probably of Pleistocene age (Gardens Basalt of Ford and others, 1963). In the vicinity of Lake Britton also, basalt like that of the Warner rests on lower or middle Pliocene lake-bed deposits. On Highway 89, 0.8 mile north of the bridge across Lake Britton, the lower 10 to 15 feet of the basalt consists of pillow lava and associated hyaloclastite formed by granulation of the hot lava where it entered water. The lava is conformable with the bedding in the underlying sediments, and poorly consolidated sediment was squeezed up into the fragmental base of the lava. It is thus unlikely that the age of this lava is very different from that of the underlying sediment. Elsewhere, however, as along Highway 299 a mile west of the Hat Creek bridge, Warner Basalt can be seen resting unconformably on the same series of lake-bed deposits, which had been slightly tilted and eroded before they were covered by the lava flows. Thus even in the small area immediately around Lake Britton, there appears to be a considerable range in the age of the basalts. Farther south, at the north end of the Sierra Nevada, Warner Basalt lies unconformably on the Penman Formation, which is probably of early Pliocene age (Durrell, 1959, p. 177–180). All that can be certainly said of these lavas is that they are later than the sediments; they could conceivably be as old as middle Pliocene. In the western part of the Prospect Peak quadrangle, however, the Burney Basalt rests against the eroded edges of fault blocks of andesite that is in turn younger than the Tuscan Formation, of late late Pliocene age, and it appears very unlikely that the Burney Basalt is older than very early Pleistocene. Thus flows of the Warner Basalt probably range from Miocene to Pleistocene in age. Gay and Aune (1958, footnote to stratigraphic table on explanatory data sheet) came to the same conclusion.

The largest continuous exposure of the Warner Basalt is that of the Gardens Basalt on the high plateau, commonly called The Gardens or The Devils Garden, that stretches from Alturas westward more than 20 miles and northward more than 25 miles, with extensions reaching far westward and northward on the south and northeast side of Clear Lake Reservoir. The total area of the plateau is in the vicinity of 700 square miles. Other extensive areas of Warner Basalt are found in other parts of the region. On Highway 299 one drives from west of Burney to the rim of Hat Creek Valley, a distance of 9 miles, continuously over the surface of the Burney Basalt.

The thickness of the Warner Basalt varies considerably, even over short distances. In the edge of the plateau near Alturas, the Warner Basalt ranges in thickness from 15 to more than 360 feet (Russell, 1928, p. 418–419). Powers (1932, p. 267) believes that the average thickness in the area mapped by him is probably a little more than 100 feet. Individual flow units range from less than 2 feet to more than 50 feet, and probably average 4 to 5 feet. Thin units are vesicular throughout, but thick ones may be very dense in their middle and lower parts. Pipestem vesicles are common at the base of flow units, but in the upper parts the vesicles tend to be spheroidal, with forms characteristic of pahoehoe. The surface forms of the flows also are typical of pahoehoe. The surface as a whole is gently undulating, the undulations being mostly part of the original surface, but to a lesser degree the result of later faulting. In some areas tumuli are common. Ropy surfaces can be seen in places.

In some areas, as on the plateau just east of the Hat Creek fault scarp in the Prospect Peak quadrangle, the vents of the Warner Basalt are marked by small- to moderate-sized cinder cones. Elsewhere, very low shields, sometimes with small amounts of spatter still preserved near their summits, were built over the vents. For the most part, however, the vents were probably fissures along which only very small amounts of spatter accumulated, as at the vents of the Recent Hat Creek flow, described on a later page. Most of these vent structures have since been destroyed by weathering and erosion, or were buried by outwelling lava in a late stage of the eruption, and they can no longer be found.

In hand specimens the Warner Basalt generally is medium to light gray, with strikingly coarse grain and, under the hand lens, with a distinctly diabasic appearance. Small yellowish-green grains of olivine are abundant in most specimens, and occasionally small phenocrysts of feldspar are present. Under the microscope, the texture is usually intergranular to subophitic, with pale-brown augite occupying the interstices between the feldspar grains. Chemically, the rocks are undersaturated, containing normative olivine, and are moderately high to very high in alumina. In two analyses listed by Anderson (1941, p. 387) alumina is 18.5 and 18.2 percent, and total alkalies approximately 2.3 percent, with potash very low. A sample collected in a railway cut at Tionesta by C. W. Chesterman contains 18.5 percent $Al_2O_3$ (Yoder and Tilley, 1962, p. 362). However, one collected by Kuno (1965, p. 306) from the basalt overlying bright-red soil in the cut on Highway 395, just east of the Pit River bridge 3½ miles northeast of Alturas, contains only 16.8 percent $Al_2O_3$.

The most characteristic feature of the Warner Basalt is diktytaxitic structure (Fuller, 1931, p. 116), in which many open spaces exist in the network of plagioclase plates, as though a late-stage fluid had drained away from between them. Actually, although diktytaxitic structure is very common in the Warner Basalt, it is not always present; furthermore, it is present in many other basalts in the area, both older and younger than the Warner, as in some basalts of the Cedarville Series, and among the upper Pleistocene and Recent flows, both in the Modoc Plateau region, and in the Cascade Range. It appears to be characteristic of high-alumina basalts in which feldspar reaches saturation and starts to crystallize at an early stage of cooling, rather than of any particular stratigraphic or structural unit. The uniformity in texture and mineral composition of rocks of this magma type, throughout the period from Miocene to Recent, is striking and noteworthy.

### Pleistocene and Recent Volcanic Rocks Other Than Warner Basalt

In the region just northeast and east of Lassen Volcanic National Park, there are many small shield volcanoes and lava flows associated with cinder cones, and some steeper lava cones that are younger than the widespread plateau basalts. The rocks range from olivine basalt, through basalt, to basaltic andesite and andesite. Among the steeper cones are Prospect and West Prospect Peaks, at the north edge of Lassen National Park, and Sugarloaf, on the west edge of Hat Creek Valley a few miles farther north. All three have cinder cones at their summits. These volcanoes are close to the Cascade Range, and perhaps should be included with it. Farther east the cones are all flatter, and most of them are typical shields of Icelandic type. Among them are Cal Mountain, Cone Mountain, and Crater Lake Mountain, just north of Highway 44 in the Harvey Mountain quadrangle. Many of them, like Cone Mountain, are crowned by a small cinder cone. Crater Lake Mountain is a typical shield, 6 miles across, containing at its summit a double collapse crater that holds a small lake. South of the highway, rows of cinder cones aligned in a north-northwest direction mark the vents of basaltic block-lava flows, the steep edges of which can be seen near the highway. Northward and eastward the abundance of post-Warner volcanic rocks decreases, and volcanoes later than the Gardens Basalt are nearly absent in the northeastern quarter of the Modoc Plateau region.

East of Highway 89, and 6 miles southeast of its junction with Highway 299, Cinder Butte is a shield built against the base of the Hat Creek fault scarp. The position of the vent was probably controlled by one of the faults of the Hat Creek system. Another shield, 9 miles to the northeast and visible from the lookout point on Highway 299 above the Pit River Falls, appears to have been the source of the lava flow that descended the Pit River canyon at that point and now constitutes the ledge of the falls. Like that of Cinder Butte, the vent that fed the shield appears to have been localized by a fault belonging, in this case, to the Butte Creek system.

It has already been pointed out that the volcanics of the Lava Beds National Monument belong to the Modoc Plateau region rather than to the Cascade Range or the Medicine Lake Highland. Actually, however, it may be more accurate to consider that the Modoc and Cascade provinces overlapped during Quaternary time. Certainly, in the region just northwest of Lassen Volcanic National Park, the late Pleistocene and Recent basalt and quartz basalt flows are identical in type to those found to the east in the Modoc region, and except for the quartz inclusions in some flows, are very much like the Warner Basalt.

Some of the eruptions in the Modoc Plateau region are very recent, though with the exception of that of Cinder Cone in the northeastern corner of Lassen Volcanic National Park, mentioned earlier, none of them are historic. On a line extending northwestward from Cinder Cone, a flow of basalt block lava from a vent between Prospect and West Prospect Peaks is so very fresh, and its surface is so well preserved, that it cannot be more than a few thousand years old. On the same line lie the vents of the Hat Creek flow, believed by Anderson (1940) to be less than 2,000 years old. The flow occupies the floor of Hat Creek Valley from south of Old Station northward for more than 16 miles. Highway 89 lies on its surface or close to its edge for most of its length. The flow is pahoehoe, with a typical undulating surface, in part ropy, and with many tumuli. Some of the latter are conspicuously displayed along Highway 44 where it crosses the flow east of its junction with Highway 89. Along much of the eastern margin of the flow is a scarp, up to 15 feet high. Although it lies along the base of the Hat Creek fault scarp, the scarp on the flow is not due to recently renewed movement on the fault, but is a slump scarp resulting from lowering of the surface of the central part of the flow as the lava drained away down the valley and shrank due to loss of gas and cooling. The Subway Cave is one of several similar caves known in the flow (Evans, 1963). It is part of the main feeding tube of the flow, formed by the draining away of lava out of the tube at the end of the eruption. It can be followed for a distance of 2,300 feet, and in places is as much as 50 feet in diameter and 16 feet high. The flat floor, which represents the congealed surface of the last fluid lava that flowed through the tube, in places shows the clinkery surface characteristic of aa—a common feature in pahoehoe tubes. The Hat Creek flow is a fissure eruption. Its vents lie along a line trending slightly west of north a mile southwest of Old Station. Spatter cones built along the fissure range from a few feet to 30 feet high.

The lava surfaces north and east of Hambone Butte, 25 miles north of Lake Britton, are very fresh and well preserved, and may be nearly as young as the Hat Creek flow. The lava appears to have come from a vent, or vents, on the south flank of the Medicine Lake Highland.

### Quaternary Sedimentary Rocks

Faulting and volcanism were essentially continuous in the Modoc Plateau region from Miocene to Recent time. These, together with climatic changes, brought about disruptions of drainage and changes of stream gradient and regimen, which in turn resulted in the formation of lakes and the deposition of lake and stream sediments. The sedimentary deposits include fanglomerates, stream-laid alluvium and terrace deposits, and tuffaceous sandy, silty, and diatomaceous lake beds, and, in the high mountains, glacial moraines and outwash. Lake deposits occupy broad areas in the Fall River Valley, Big Valley, the valley of the South Fork of the Pit River, the Madeline Plains, around the north end of Lake Almanor, the region around the Klamath and Tule Lakes, and smaller areas in other basins. Still other basins that appear to be wholly floored by alluvium may be underlain by lake deposits. Deposition of both lake sediments and alluvium is continuing in these basins today.

### Structure

The dominant structure of the Modoc Plateau region is the very large number of northwest- to north-trending faults (fig. 4), many of which are so recent that the scarps are still well preserved. Most of the faults are normal, with little or no suggestion of strike slip; but Gay (1959, p. 5) and his coworkers have found evidence of major right-lateral movement on the Likely fault, which extends southeastward from near Canby for 50 miles, to the northeastern part of the Madeline Plains. (See California Div. Mines, 1958, Alturas sheet, Geologic Map of California.) Along this fault, sag ponds and offset drainage lines are still visible. On the normal faults, either the east or the west side may be downthrown. Some fault blocks are tilted, with a visible fault scarp on only one side, but others are bounded by fault scarps on both sides. The amount of displacement varies from a few feet to more than 1,000 feet. Striking fault scarps are so numerous that it is difficult to single out any for special mention. Among them are: the scarp more than 1,300 feet high on the east side of Lookout Mountain, 5 miles north of Burney; the step-fault scarp 1,800 feet high on the west side of Fort Mountain, 3 miles northeast of the Highway 89 bridge over Lake Britton; the scarp ascended by Highway 299 at the east edge of Fall River Valley; the 2,000-foot scarp on the west side of Mahogony Mountain, east of Highway 97, 7 miles south of Dorris; the series of spectacular east-facing scarps west of Tule Lake that are visible from Lava Beds National Monument; and the series of scarps near Highway 139 southeast of Tule Lake. A low, but beautifully preserved, scarp is visible just east of Highway 89 about 4½ miles north of its junction with Highway 299.

Figure 4. Topographic map of part of the Prospect Peak quadrangle, showing the Hot Creek fault scarp along the eastern edge of Hot Creek Valley. The plateau on the right of the scarp is capped with Burney Basalt. Sugarloaf Peak, on the left, is a late Pleistocene cone built largely of andesite block lava flows. The valley is floored by the Hot Creek lava flow, which only a few thousand years ago poured out of inconspicuous vents located 2 miles north of the south boundary and 1 mile east of the west boundary of the figure.

The fault scarp along the east side of Hat Creek Valley also deserves special comment. At its highest point, the scarp, which is clearly visible from Highway 89 and is ascended by Highway 44, rises more than 1,000 feet above the surface of the Hat Creek lava flow. The fault is a complex system of subparallel *en echelon* fractures, the displacement increasing on one as it decreases on the adjacent one, with the blocks between them commonly constituting inclined ramps (fig. 4). The Butte Creek fault system, 3 miles farther east, shows a similar pattern (Macdonald, 1964). Frequent small earthquakes are reported from the Hat Creek region, indicating that the Hat Creek fault probably is still active.

### Hydrology

Brief mention should be made of some of the features of the hydrology. Throughout much of the region, the high permeability of the surface rocks, typical of basaltic terranes, results in a nearly complete lack of surface drainage. However, the underlying rocks are commonly much less permeable, and the rocks of the Cascade Range constitute a barrier to the westward movement of the ground water. The result is a water table that ranges in altitude from about 4,000 to 4,100 feet through much of the Modoc Plateau region. Above about 4,000 feet, the Pit River and its tributaries and many of the other streams are losing water to the ground, but below that altitude they are gaining water (R. H. Dale, oral communication, 1965).

Lost Creek disappears completely within a short distance of the place where it flows onto the surface of that Hat Creek lava flow, and Hat Creek itself loses large amounts of water to the same lava flow along the upper part of the valley; but the water appears again at the Rising River springs (eastern side of the Burney quadrangle), where the lower end of Hat Creek Valley is blocked by less permeable older rocks. The upper stretches of Burney Creek lose water to the permeable Burney Basalt and a mile above Burney Falls the streambed is usually completely dry; but 200 million gallons of water issue daily from the streambed within five-eighths of a mile above the falls and in the face of the falls in McArthur-Burney Falls State Park, where the base of the lava is exposed resting on the less permeable rocks beneath.

The Fall River Springs, 7 miles north of Fall River Mills, is one of the largest spring groups in the United States, with a flow of about 1,290,000,000 gallons a day. This huge discharge is particularly striking in view of the low rainfall in the surrounding region. Studies of groundwater gradients by the U.S. Geological Survey indicate that the water is moving southward from the Tule Lake and Clear Lake Reservoir areas, 50 miles to the north, beneath and around the Medicine Lake Highland (R. H. Dale, oral communication, 1965).

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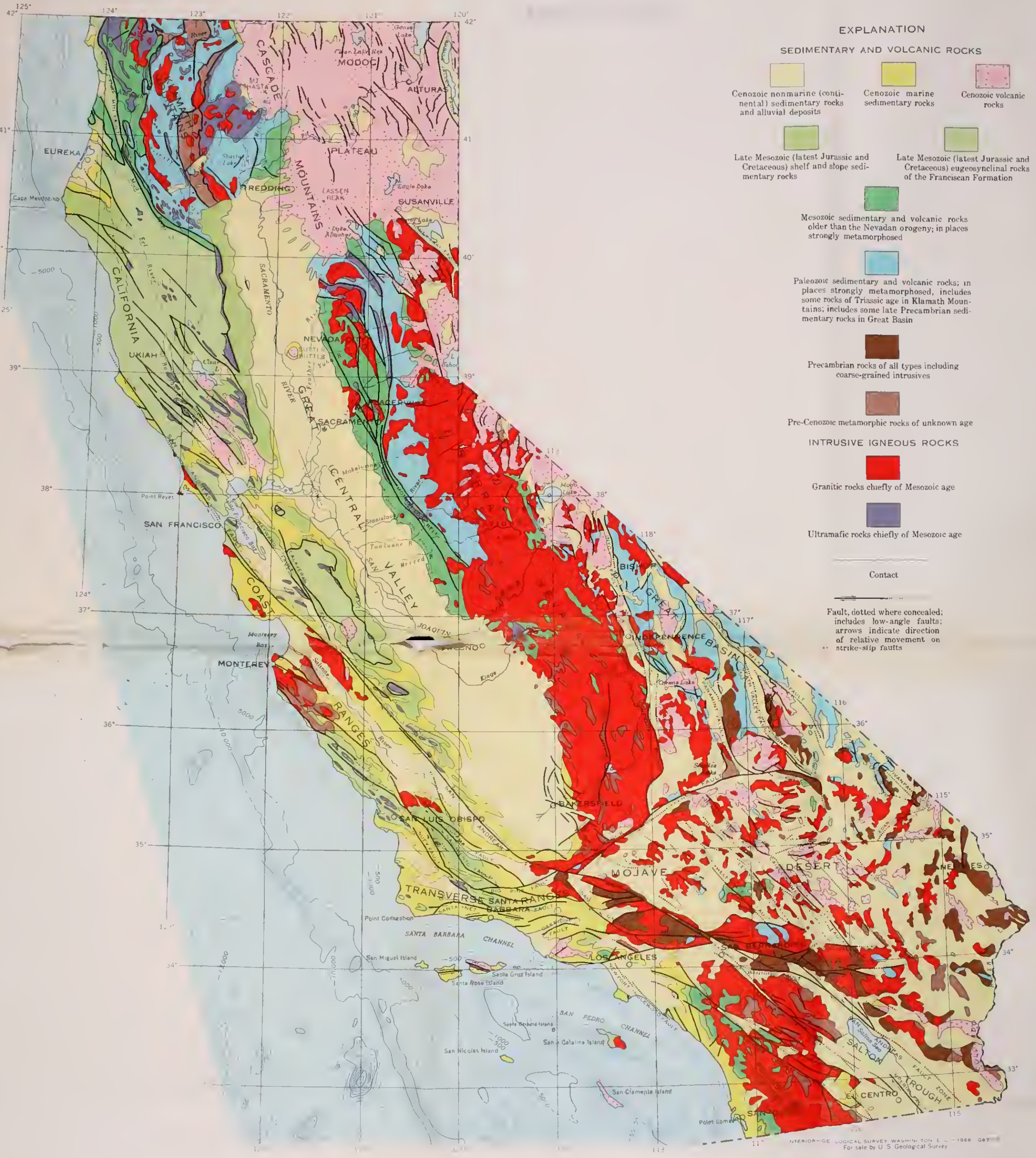
Photo 19. Basalt pillow lava (Warner basalt) resting on diatomaceous lake sediments along Highway 89 just north of the bridge across Lake Britton. The pillows lie in a matrix of hyaloclastite. Diatomite has squeezed up into the fragmental base of the flow.

Photo 20. Hornito (rootless spatter cone) built on the surface of a pahoehoe lava flow in Lava Beds National Monument.

DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



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## EXPLANATION

### SEDIMENTARY AND VOLCANIC ROCKS

🟨 Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits

🟨 Cenozoic marine sedimentary rocks

🟪 Cenozoic volcanic rocks

🟩 Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks

🟩 Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation

🟩 Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed

🟦 Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin

🟫 Precambrian rocks of all types including coarse-grained intrusives

🟫 Pre-Cenozoic metamorphic rocks of unknown age

### INTRUSIVE IGNEOUS ROCKS

🟥 Granitic rocks chiefly of Mesozoic age

🟪 Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

# GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1 2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND
1000 FEET DATUM IS SEA LEVEL

1966