Pleistocene Glaciation

LASSEN VOLCANIC NATIONAL PARK

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INTRODUCTION

Lassen Volcanic National Park (figure 1) in northeastern California is noted primarily for volcanic terrain, yet much of the geomorphology can be explained only in terms of Pleistocene glaciations (figures 2-4). Both erosional and depositional glacial landforms "overprint" most of the volcanic foundation and give beauty and diversity to the Lassen Park landscape. The wide distribution of morainal deposits, outwash fans, and erosional features indicates that the area supported large mountain ice caps several times during the Pleistocene Epoch (photos 1-9).

Numerous cirque and valley glaciers characterized the waxing and waning phases of each period of Pleistocene cooling that culminated in an ice blanket. From these major ice blankets, which were approximately centered on what is now the Lassen Park area, glaciers spread in a generally radial pattern in every direction, and down fifteen major valleys. Two of the more conspicuous volcanoes in today's landscape—Lassen Peak and Chaos Crags—had not yet been extruded, so the area looked quite different during the Pleistocene Epoch compared to the present landscape. In fact, the primary glacial accumulation area was around Mount Tehama (figure 2), a large 3,300 m (11,000 ft)-high composite volcano that occupied what is today the southwest corner of Lassen Park. Mount Tehama (also named Brokeoff Volcano) is represented today only by remnant peaks, including Brokeoff Mountain and Mount Diller. The large volcano's demise was the result of volcanic collapse, accompanied by glacial and fluvial erosion. From the Mount Tehama area, the Pleistocene ice divide in the Lassen Park area trended basically eastward, across the central plateau and around Juniper Lake to the ridges along the eastern boundary of the Park. Secondary accumulation zones were on two of the area's shield volcanoes, Mount Harkness and Sifford (Red) Mountain; these volcanoes supported their own small ice fields which merged with the general ice blanket.

The main effects of glaciation in the Lassen Park area were the deepening of major valleys, the removal of bedrock from large parts of the landscape, and the creation or enlargement of hundreds of lake basins. The Pleistocene glaciers deposited their till as ground moraines, lateral moraines, and outwash fans at elevations below about 1800 m (6,000 ft). Most moraine deposits are outside of the present Park boundaries.

PREVIOUS GLACIATION STUDIES

The first person to describe glacial activity in the Lassen Park area was W.H. Brewer in 1864. Brewer mentioned that "glaciers once streamed down from Lassen's Peak, on every side. The rocks are furrowed and polished by them, canyons show their traces everywhere, but all have passed away" (Brewer, 1966, p. 466).

A year later, J.S. Whitney (1865, p. 316) described in more detail the prominent directions of glacier flow:

"On all sides of Lassen's Peak, evidence of the existence of former glaciers was observed. The traces of them were most numerous and best preserved at an altitude of from 7,500 to 8,000 feet; but they occurred in abundance between 6,000 and 9,000 feet. An immense glacier formed on the south slope, just below the farthest cone, and flowed south, covering a table several miles in extent and descending to the canyons of the Feather River. Another one originated along the divide east of the Peak, and descended into the valley of Hat Creek." However, it is now known that Lassen Peak is only about 11,000 years old (Crandell and Mullineaux, 1970), and it could not have been a center of glacier radiation.

The first major consideration of glacial inheritance of the Lassen Park area was in a detailed study of the bedrock geology by Howel Williams in 1932. In addition to devoting several pages exclusively to glaciation, numerous scattered comments throughout Williams' report describe the effects of glacial erosion and deposition.

The work of D.R. Crandell, who mapped the glacial limits in the western one-third of Lassen Park and adjacent Lassen National Forest in 1972, is the most thorough published study of the glacial history of the Lassen area. Crandell distinguished three ages of till in the deposits he mapped. By correlating the Lassen till characteristics with the characteristics of tills in the Sierra Nevada, he identified pre-Tahoe, Tahoe, and Tioga till (middle to late Pleistocene age). Age differentiation was based on soil characteristics, specifically the thickness of weathering rinds on volcanic stones, the presence or absence of textural-B horizons, the depth of oxidation, and soil color. Crandell concluded that during each of the established glaciations, the primary glacial accumulation region in the western part of Lassen Volcanic National Park was on the sides of old Mount Tehama, not around Lassen Peak.

In 1975, the writer made a comprehensive and detailed study of glaciations and glacial geomorphology in the Lassen Park area (Kane, 1975, unpublished report). Most of the fieldwork and lab time devoted to unraveling the glacial geomorphology was spent in mapping glacial landforms, and in relative-age dating the depositional tills and outwashes. Each of the twenty or so valleys in the area were investigated, mostly from the ground, but also by means of aerial photographs, topographic and geologic maps, and low-level flights in small aircraft. From such field evidence as the location of lateral and recessional moraines, the distribution of ground moraines, the directions of glacial striations, and the siting and aspects of cirques and glacially quarried outcrops, it has been possible to establish with some degree of accuracy both the maximum extents of the Tahoe and middle Tioga ice caps, and the location of the middle Tioga ice divides. That 1975 study was supplemented by additional fieldwork and sample analyses in 1977 and 1980.

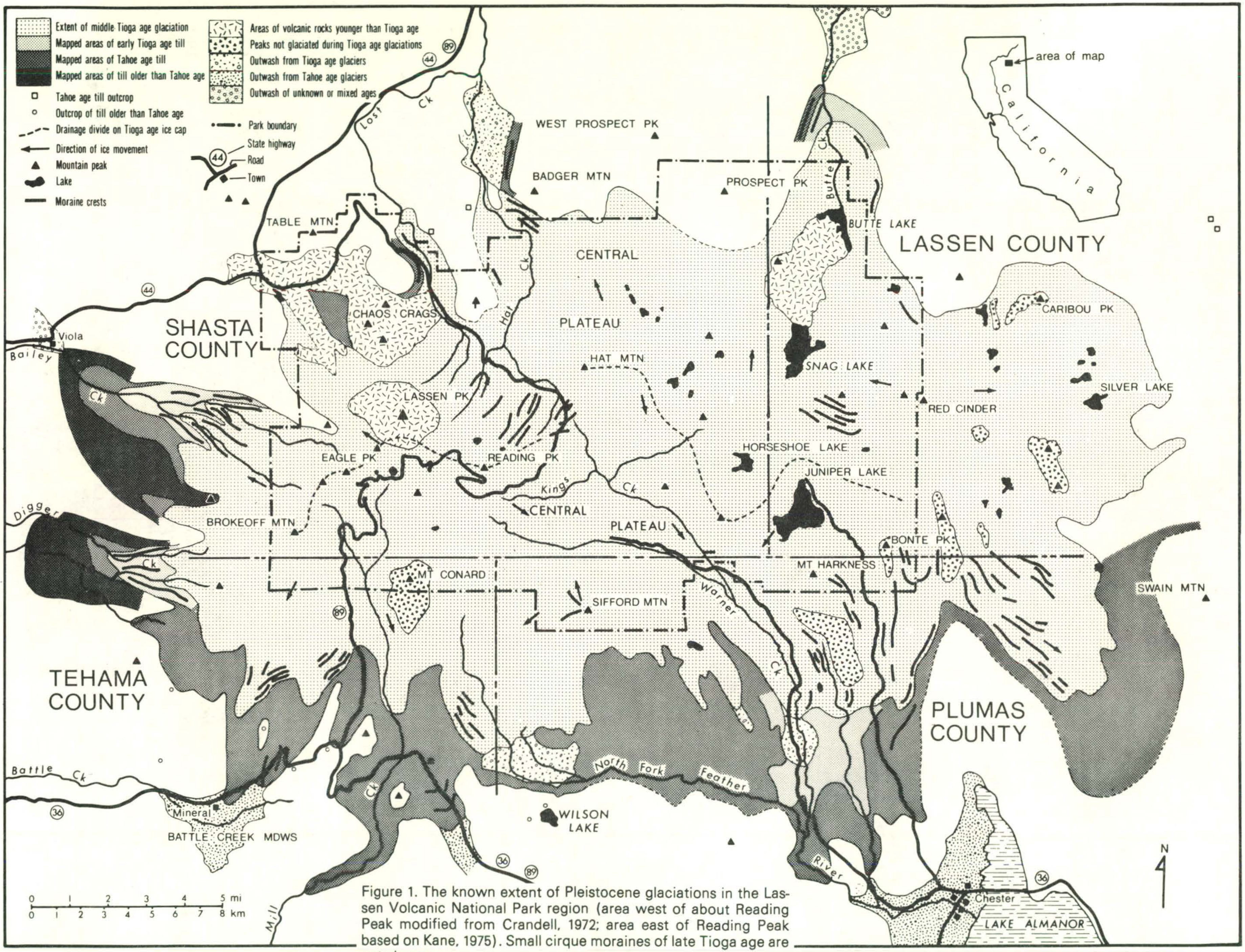

Figure 1. The known extent of Pleistocene glaciations in the Lassen Volcanic National Park region (area west of about Reading Peak modified from Crandell, 1972; area east of Reading Peak based on Kane, 1975). Small cirque moraines of late Tioga age are not shown.

TILL AGES AND GLACIAL CHRONOLOGY

Because erosion rates are high in steep mountainous terrain, glacial deposits are not well preserved in places like the Rocky Mountains, the Sierra Nevada, and the Cascade Range. With some exceptions, only deposits from the smaller-scale advances *within* the Wisconsin Stage are preserved to any significant degree. Older till might be found in scattered patches or as low moraines in some places. However, it is usually not possible to establish how many glacial advances mountain landscapes endured because the evidence (recorded as different ages of till) has been eroded away. The landscape of Lassen Park and other glaciated alpine areas like Lassen reflect at least two million years of glacial and fluvial erosion—not just the few 100,000 years suggested by the ages of the preserved tills and outwash deposits.

TABLE I

PROVISIONAL GLACIAL SEQUENCE AND CORRELATIONS OF CALIFORNIA AND NORTH AMERICAN CONTINENTAL GLACIATION

Geologic Epoch	Stage of mid-continent North America glaciation	CALIFORNIA GLACIAL DEPOSITS: Sierra Nevada southern area	Lassen Volcanic Nat'l Park Area	Sierra Nevada Tahoe Area	Klamath Mountains	Approximate ages for the central and southern Sierra Nevada (BP = years before present)
HOLOCENE	Neoglacial	Matthes till Recess Peak till		till	till till	700 BP to present 2000-4000 BP
HOLOCENE	Climatic Optimum (warmest climate)					(4000-9000 BP)
PLEISTOCENE, late	Wisconsin Late	Hilgard Tioga Tenaya	late Tioga till middle Tioga till early Tioga till	Frog Lake till Tioga till	Morris Meadow till	9000-11,000 BP 11,000-25,000 BP 25,000-29,000 BP
PLEISTOCENE, late	Middle					
PLEISTOCENE, late	Early	Tahoe	Tahoe till		Rush Creek till	45,000-60,000 BP
PLEISTOCENE, middle	Illinoian	Mono Basin till	pre-Tahoe till		Alpine Lake till	about 130,000 BP
PLEISTOCENE, middle	Kansan	Casa Diablo till		Donner Lake till	Swift Creek till	about 400,000 BP
PLEISTOCENE, early	Nebraskan					
	Pre-Nebraskan	Sherwin till McGee till Deadman Pass till	(Deer Creek till)			about 750,000 BP about 2.5 million BP between 2.7 & 3.1 million BP
	California sources:	Blackwelder (1931) Sharp & Birman (1963) Birman (1964) Curry (1966)	Crandell (1972) Kane (1975) (Hilton & Lydon, 1976)	Birkeland (1964)	Sharp (1960)	Birkeland & others (1971) Sharp (1972), Woods (1976)

A glacial sequence chart and a list of the glacial advances usually recognized as having deposits preserved in the Sierra Nevada and Klamath Mountains are shown on table 1. The Sierra Nevada glaciations, especially, have been extensively studied and the names used there for separate glacial stades have been standardized since the early 1930's (Blackwelder, 1931; Sharp and Birman, 1963; Birman, 1964; and Bateman and Wahrhaftig, 1966). Also included in the table are the suggested time correlations and informal till names for the Lassen area (based on and modified from Crandell, 1972; and Kane, 1975).

Five glacial advances are recognized in Lassen Volcanic National Park (table 1, figure 1). Four advances occurred during the Wisconsin Stage, and one probably occurred during the older Illinoian Stage. Many other glacial episodes no doubt occurred, but their deposits are either no longer preserved or have not yet been well established or discovered in the geologic record.*

WISCONSIN STAGE REGIONAL SNOWLINE

The regional (average orographic) snowline of an area is approximately equivalent to the elevation of the 0°C (32°F) isotherm for the warmest month

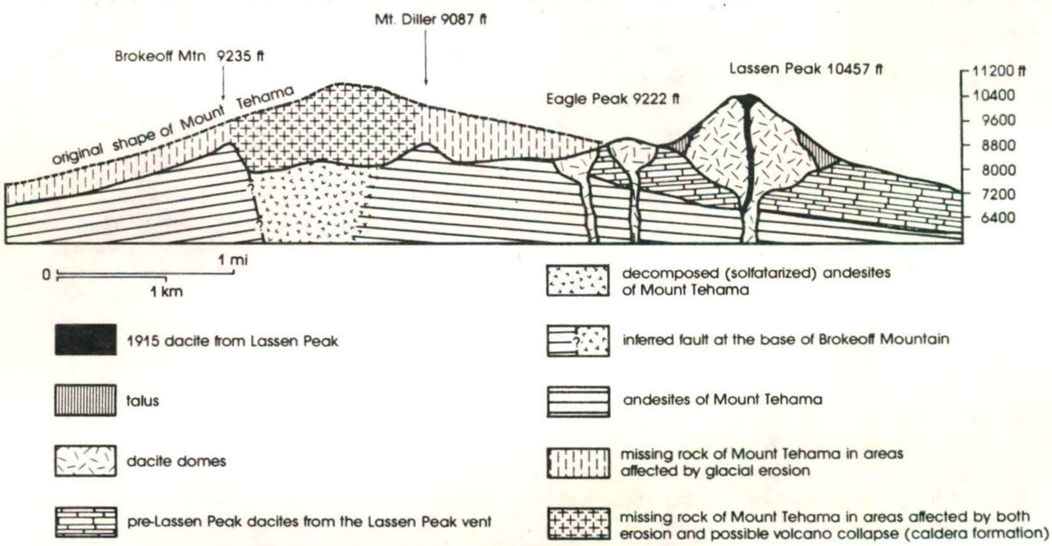

Figure 2. Cross section showing the presumed original profile of Pleistocene Mount Tehama; the large-scale removal of "flank material" and the correlation of lithology and topography point out the important role of differential (glacial) erosion upon the volcano (figure modified from Kane, 1980).

*There is also some evidence for an even older (?) pre-Nebraskan till (Hilton and Lydon, 1976); this till occurs far to the west of Lassen Park and is not discussed in this paper, although it is included in table 1.

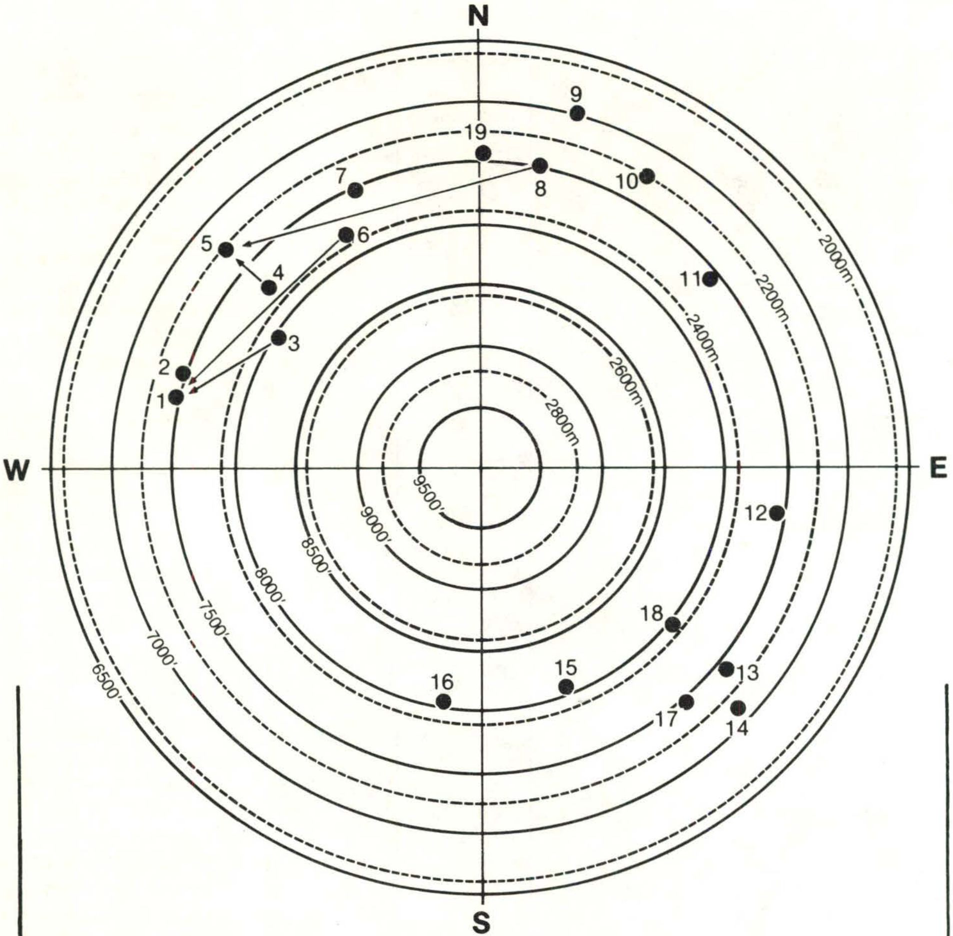

Figure 3. Exposure-height diagram showing the elevations and aspects of Wisconsin-age cirques in western Lassen Volcanic National Park. Diagram is arbitrarily centered on the 10,000-foot elevation contour. Cirque elevations are corrected for lake depths where appropriate. Arrows connect what are probably two-storied cirques.

Cirques are identified by number: 1-below Soda Lake (Blue Lake Canyon), 2-north branch of South Fork Bailey Creek, 3-above Soda Lake (Blue Lake Canyon), 4-south branch of South Fork Bailey Creek (east tributary), 5-south branch of South Fork Bailey Creek, 6-Soda Lake (Blue Lake Canyon), 7-West Fork Manzanita Creek, 8-south branch of South Fork Bailey Creek (west tributary), 9-Paradise Meadows (West Fork Hat Creek), 10-Cliff Lake (East Fork Hat Creek), 11-Shadow and Terrace Lakes (East Fork Hat Creek), 12-east side of Reading Peak, 13-southeast side of Reading Peak, 14-Crumbaugh and Cold Boiling Lakes (North Arm Rice Creek), 15-Emerald Lake (Little Hot Springs Valley), 16-Lake Helen (Little Hot Springs Valley), 17-Forest Lake (upper Mill Creek), 18-Ridge Lakes (West Sulphur Creek), and 19-Mount Harkness.

Editor's note: An exposure-height diagram is a commonly-used plot to depict how the elevations of cirques vary with compass direction (that is, the direction the cirques "face"). Cirques are at low elevations on the shady, north slopes of mountains; they are at higher elevations on the sunny, south slopes.

(Flint, 1971, p. 65). Applying this principle to the Mount Shasta area, for instance, and using weather data for Mount Shasta City, elevation 1,080 m (3,550 ft), with mean July temperature of 20°C (68°F), the elevation of the 0°C isotherm is 3,900 m (12,900 ft) (using a Normal Lapse Rate of 0.65°C/100 m). This value is in agreement with the observed snowline elevation of 3,960 m (13,000 ft), which is based on the sites and aspects of the mountain's glaciers (American Geographical Society, 1958, p. 31a.1). Lassen Park has no present-day glaciers upon which to substantiate this type of calculation, but assuming that the Normal Lapse Rate does not change radically in the intervening 115 km (70 mi), and using the weather data for Mineral, the regional snowline for Lassen Volcanic National Park is at approximately 4,200 m (13,800 ft), well above Lassen Peak.

The Pleistocene regional snowline of the Lassen Park area was much lower, of course, during the periods of ice cap growth and glacial advance. In practice, such a regional snowline can be estimated from the average elevations of cirque floors (figure 3). Based on the elevations of nineteen cirque floors (figure 3), the Wisconsin* regional snowline in the western Park area was about 2,290 m (7,500 ft); north-facing cirques developed as low

*"Wisconsin" is taken to include here the Tahoe, early Tioga, and middle Tioga stades. The inference is that the cirques of the Lassen Park area were excavated and used by glaciers of all three stades, a reasonable inference used by other investigators in other areas; see, for example, the work of Wahrhaftig and Birman (1965, p. 304) dealing with the Sierra Nevada.

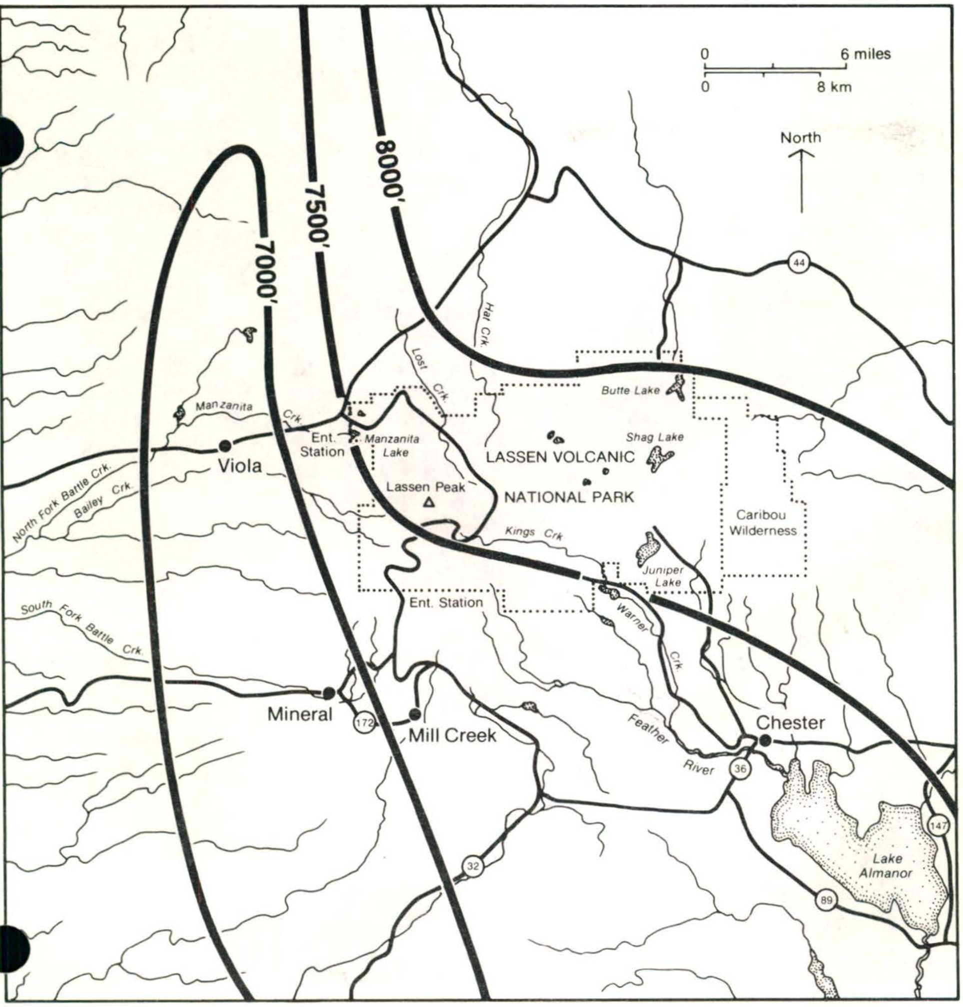

Figure 4. Elevation of the Wisconsin regional snowline (in feet) for the Lassen Volcanic National Park area.

as 2,135 m (7,000 ft); and south-facing cirques were about 305 m (1,000 ft) higher at 2,440 m (8,000 ft).

The Lassen Volcanic National Park area with contours of the Wisconsin regional snowline superimposed is shown on figure 4. The position of these contours is based on the elevations of cirques found in the western part of Lassen Park (figure 3), on Turner Mountain 18 km (11 mi) south-southeast of Brokeoff Mountain (Crandell, 1972, p. C186), and on Jacks Backbone and Crater Peak about 29 km (18 mi) north-northwest of Brokeoff Mountain (Macdonald, 1963). The position of the 8,000-ft (2,440-m) contour in the Park area is based on the fact that neither Badger Mountain at elevation 2,173 m (7,127 ft) nor Prospect Peak at elevation 2,543 m (8,338 ft) supported middle Tioga glaciers (or Tahoe glaciers). The regional snowline rose at a gradient of 19 m per kilometer (100 ft per mile) from Turner Mountain to the Brokeoff Mountain area, and at a gradient of at least 12 m per kilometer (65 ft per mile) between Brokeoff and Prospect Peaks.

In all probability the regional snowline was a few hundred meters lower than indicated by figure 4 because cirque-formation is only the initial expression of a falling snowline and one of the last expressions of a rising snowline in many glacial environments. At the height of a glacial episode in areas like Lassen Volcanic National Park and the Sierra Nevada, glacial accumulation zones were in mountain ice caps which buried the cirques that were formed during an earlier glaciation. Accordingly, cirque-floor-based snowlines are not an indication of the lowest position of regional snowlines.

DISTRIBUTION OF WISCONSIN STAGE ICE CAPS

Maximum Extent

With each significant lowering of the snowline during the Pleistocene Epoch, ice began to accumulate as cirque glaciers in the western highlands from Mount Tehama to Reading Peak. As the climate cooled and the budgets of cirque glaciers increased, they grew into valley glaciers. Probably contemporaneous with this stage, ice also began to accumulate on the central plateau and in the eastern ridges (between Bonte Peak and Red Cinder). With a continued drop in the snowline, valley glaciers and plateau ice merged into a more or less continuous ice cap, although the higher peaks and ridges probably remained above the glacial blanket. At the conclusion of a glacial episode and under a rising snowline, annual net ablation reversed the cycle. The ice cap then decayed into isolated masses of relatively stagnant plateau ice and still-active valley glaciers. The valley glaciers eventually retreated to cirque glaciers, and perhaps melted away altogether during the interglacial periods.

At its greatest extent, the middle Tioga ice cap, with its associated "outlet" glaciers, covered a total area of about 680 sq km (262 sq mi). It is more difficult to estimate the area of the Tahoe ice cap because Tahoe tills are only partly preserved and exposed. Extrapolating from those deposits that were mapped, it can be inferred that the Tahoe ice cap had an area of about 1,010 sq km (390 sq mi). A tabulation by drainage basin of these areas is given in table 2; figure 1 depicts the extent of middle Tioga ice, the distribution of outwash and other recognized tills, and additional glacially-related features.

As can be seen from table 2 and figure 1, the middle Tioga ice blanket is the only one for which a "closed reconstruction" is possible. For this ice cap, the most important individual drainage basins were Butte Creek and Warner Valley. Together they contained about one-third of the total ice cap area. The accumulation zones for these two drainage routes were on, or around, the margins of the vast central plateau. In particular, the Butte Creek basin was fed by glaciers that accumulated along the ice divide running south from Hat Mountain (figure 1) and from the Horseshoe Lake depression. This basin probably received about the same amount of ice from the eastern ridges. The Warner Valley iceshed drained the southern central plateau, the Juniper Lake region, and the plateau sides of Reading Peak, Sifford Mountain, and Mount Harkness. Next in importance and accounting for about one-fourth of the glaciers, were the northern and southern Caribou Wilderness areas, which border the Lassen Park area on the east.

TABLE 2
DISTRIBUTION OF MIDDLE TIOGA AND TAHOE GLACIERS BY DRAINAGE BASIN AND LOWEST ELEVATIONS REACHED

	Middle Tioga Icecap[1]			Tahoe Icecap[2]		
	Area		Elev. Reached	Area		Elev. Reached
	km^2	(mi^2)	m (ft)	km^2	(mi^2)	m (ft)
SACRAMENTO RIVER						
N. Fork Battle Creek						
Manzanita Creek. . .	21	(8)	1710 (5600)	-		(covered)
Bailey Creek	26	(10)	1710 (5600)	37½	(14½)	1400 (4600)
Digger Creek	19½	(7½)	1680 (5500)	30	(11½)	1435 (4700)
S. Fork Battle Creek						
Panther Creek. . . .	2½	(1)	2010 (6600)	8	(3)	1770 (5800)
Battle Creek Meadows	18	(7)	1645 (5400)	36½	(14)	1495 (4900)
Mill Creek	46½	(18)	1495 (4900)	67	(26½)	1310 (4300)
Gurnsey Creek	0	(0)	-	5	(2)	1480 (4850)
N. FORK FEATHER RIVER						
Feather River Meadow	49½	(19)	1680 (5500)	98½	(38)	to Warner
Warner Creek	109	(42)	1535 (5025)	122	(47)	1465 (4800)
Louse & Benner Crks . .	44	(17)	1620 (5320)	59½	(23)	1465 (4800)
S. Caribou Wilderness .	57	(22)	1770 (5800)	85½	(33)	1645 (5400)
N. CARIBOU WILDERNESS. . .	65	(22)	1920 (6300)	-		<1785 (5850)
PIT RIVER						
Lost Creek.	23½	(9)	1660 (5450)	-		(covered)
Hat Creek	52	(20)	1645 (5450)	-		(covered)
Rail Canyon	27	(10½)	1800 (5950	-		(covered)
Butte Creek	119½	(46)	1740 (5700)	-		1710 (5600)

[1] the total area of the Middle Tioga icecap was about 680 sq km (262 sq mi).

[2] the total area of the Tahoe icecap, as extrapolated from those basins in which Tahoe till was mapped, is estimated to have been about 1010 sq km (390 sq mi).

These four central and eastern basins, then, included one-half of the middle Tioga ice cap area. It should be noted, however, that this would have been equivalent to much less than one-half of the ice *volume.* This is because the accumulation zones for these basins were mostly on the flattish central plateau where the ice was thin, and therefore, easily and quickly transformed into large ablation zones whenever the regional snowline rose to an elevation just above that of the plateau itself.

By contrast, the Sacramento River drainages accounted for about twenty per cent of the ice by *area,* but probably well over that percentage in terms of volume. The reason for this lies in the fact that the western ice fields accumulated on the steeper and higher slopes of Mount Tehama. These more "alpine-like" western glaciers, with their steeper longitudinal profiles and with more of their accumulation zones above the snowline, would have had longer life spans under a warming climate, larger annual budgets, and higher mean flow velocities.

Major Wisconsin Ice Divides

Orientation of glacial striations and recessional moraines indicates the existence of not just one center of ice radiation, but rather a long, somewhat sinuous ice divide that ran from Mount Tehama eastward through the central plateau to the eastern ridges located between Red Cinder and Bonte Peak. The course of the ice divide is shown on figure 1.

A break in the ice divide occurred in the vicinity of Summit Lake, south of Hat Mountain, where ice from the central plateau converged with some of the Reading Peak glaciers. Two ice centers, therefore, can be inferred: a western ice cap centered over the Mount Tehama to Reading Peak crestline, and an eastern ice cap centered north of Juniper Lake and reaching from Bonte Peak to Hat Mountain.

For the most part, the trend of the Wisconsin ice divide corresponds with present day drainage divides. The general coincidence suggests that nowhere did large amounts of accumulation-zone ice move by diffluent flow from one topographic basin into another. There were, however, four exceptions to this containment of ice in topographic basins. One is the depression between Lake Helen and Lassen Peak (cover photo), where a col above the lake indicates minor diffluence of Manzanita Creek ice into Mill Creek. The second exception is in the area just east of Hat Mountain (Echo Lake), where glacial striations and the aspects of plucked bedrock suggest that ice drained south into Warner Valley, not northeast into Butte Creek as does the present fluvial system. Thirdly, much of the ice that accumulated in the Juniper Lake basin fed into Benner Creek, whereas in the present landscape Juniper Lake drains into Warner Valley. The fourth exception was the Panther Creek basin, which was too low to have its own accumulation zone, and therefore, must have received its ice only by diffluence from adjacent basins. This basin has an anomalously high terminal moraine location as shown in table 2.

GLACIAL GEOMORPHOLOGY

The glaciation of the Lassen Park landscape was extensive and repeated throughout the Pleistocene Epoch.

Photo 1. View from Diamond Peak south down the glacial valley of Mill Creek. On the left is the west side of Mount Conard, and right of center is the asymmetrical plug-dome of Morgan Mountain. Local relief from the top of Morgan Mountain to Mill Creek is 565 m (1,850 ft). If the steeper east side of Morgan Mountain is a reflection of glacial erosion, one can infer about 185 m (600 ft) of local valley deepening by Pleistocene glaciers.

Photo 2. View of part of the southeast-facing cirque on the east side of Bumpass Mountain. The cirque headwall here rises about 215 m (700 ft) above Crumbaugh Lake, one of two tarns now occupying the cirque floor. Crumbaugh Lake averages 0.25 km (0.15 mi) across and is at an elevation of 1,497 m (7,204 ft).

Erosional Glacial Landforms

The largest features of glacial erosion in the Lassen Park landscape are the glaciated valleys or troughs. They are not as conspicuous and well known as those on the western slope of the Sierra Nevada, but they are nevertheless valleys with forms that attest to a long history of glacial modification. Many valleys of Lassen Park reflect glacial straightening (spur truncation), erosional deepening (U-shaped transverse profiles), and in some cases enhancement of preglacial longitudinal irregularities (cascades and waterfalls).

The best examples of trough forms are Mill Creek valley (photo 1) and the North Fork of Bailey Creek (Blue Lake Canyon). U-shaped valley profiles are also apparent across Warner and Hot Springs Creek valleys. In these two cases the valley sides are bounded by faults (Williams, 1932, p. 384) and, therefore, the trough depths probably are due to graben formation as well as to glaciation.

It is difficult to infer amounts of valley deepening in the Lassen Park area because of this volcanic-tectonic nature of the landscape and its intrinsic topographic irregularity. Also, one of the most useful measures of valley deepening—hanging valleys — are virtually nonexistent because of the generally radial spreading of ice. Some speculation is possible, however, for both Mill Creek and Bailey Creek valleys. In the case of Mill Creek, one clue to the degree of deepening may be in the asymmetry of Morgan Mountain (photo 1), with its relatively unglaciated west flank sloping at twenty degrees, and its more heavily glaciated eastern flank sloping at thirty-one degrees. Assuming this plug-dome volcano originally possessed a near-symmetrical profile, then the amount of deepening in Mill Creek opposite Morgan Mountain was about 185 m (600 ft). Similar nonstructural breaks in slope on Loomis Peak suggest 275 m (900 ft) of material removed by glacial action in the North Fork of Bailey Creek.

Cirques are another characteristic erosional landform, and can be found at the heads of most valleys in the western highlands of Lassen Park (photo 2). These cirques are identified by name and location in figure 3. Eighteen of the nineteen cirques are on the flanks of the divide running between Brokeoff Mountain and Reading Peak. A solitary cirque on the north-facing side of Mount Harkness is the only one identified in the eastern area of Lassen Park. A typical cirque is about 800 m (0.5 mi) across and set into a mountainside below a boulder-strewn "headwall" 120-150 m (400-500 ft) high. Most cirques are closed depressions with small tarns. Typical tarns, such as Emerald Lake and Lake Helen (cover photo), are approximately 800 m (1,300 ft) in diameter with depths less than 35 m (110 ft). Tarns are usually impounded by a bedrock lip veneered with ablation till or a small moraine. Due to the layered nature of the volcanic bedrock, the sitings of cirques probably were only approximately at the local snowlines. This structural influence is well exhibited in the North Fork of Bailey Creek.

Some places, which prior to glaciation were closed or nearly closed depressions

Photo 3. Aerial view west toward Brokeoff Mountain, elevation 2,817 m (9,235 ft), and the upper reaches of Mill (West Sulphur) Creek basin. Several features of note are shown: the solfatarized andesites of the Mount Tehama vent and summit area (right half of photo), a glacial arête (the ridge running north from Brokeoff Mountain), the truncated lava and tephra layers on both sides of Brokeoff Mountain, and the large cirque-like Pleistocene ice-accumulation area of the upper Mill Creek basin.

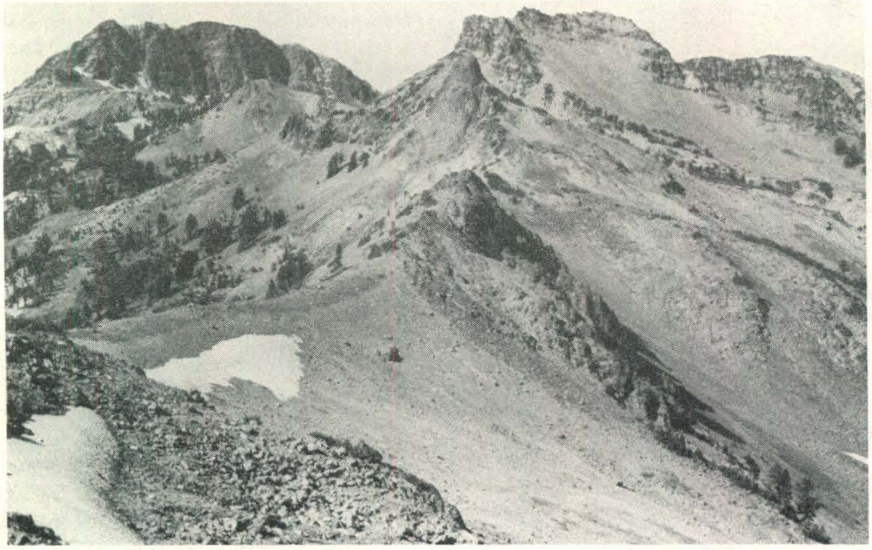

Photo 4. View southwest from Ski Heil toward Mount Diller (center background) and Brokeoff Mountain (left background). The ridge joining the three peaks is an arête, and is the drainage divide between Bailey Creek on the right and upper Mill (West Sulphur) Creek on the left. The distance along the arête is about 2 km (1.3 mi). Gently northwest dipping lava flows of the eroded Mount Tehama are visible on Mount Diller.

because of the volcanic lay of the land, served as large cirque-like, ice-accumulation areas because by chance their elevations closely matched that of the Pleistocene snowline. The best example of these cirque-like areas is upper Kings Creek Meadow, walled in on three sides by Reading Peak, old lava flows from the site of Lassen Peak, and Bumpass Mountain. The meadow served as a large accumulation site for ice that eventually fed into Warner Valley.

The entire upper Mill Creek basin was another vast ice accumulation zone for Mill Creek's glaciers (photo 3). The great volume of ice held there and the extensive amount of erosion accomplished by the Mill Creek ice field is indicated by the large bowl-like depression contained within the Brokeoff Mountain-Mount Diller-Bumpass Mountain-Mount Conard ridge. The western part of this ridge is an arête, formed between the Bailey Creek cirques on the west and the Mill Creek cirque-like feature on the east (shown in part in photos 3 and 4).

Glacial removal of bedrock was by no means confined only to the valleys. It can be inferred from the severely eroded condition of Pleistocene Mount Tehama, for example, that large volumes of bedrock were plucked away from the high-relief western highlands. This inference is based on the fact that the southwest flank of Brokeoff Mountain is a true dip slope up to a height of 2,560 m (8,400 ft), but above that elevation the topographic slope steepens and the upper 240 m (800 ft) of the peak is composed of truncated lava flows and ash layers on this *dip-slope* side (photo 3). The truncation of these dip-slope strata, first mentioned by Williams (1932, p. 245), must be explained in terms of some agent of erosion. Seemingly, the appropriate agent in this case is glacier ice. This evidence appears to indicate that *at least* "a few hundred feet of lava have been eroded above present-day Brokeoff Mountain" (Williams, 1932, p. 44), and from the sides of Mount Tehama in general.

East of the western highland area of Lassen Park, modification of the landscape by glaciation was not nearly so severe because the relatively lower elevations of the central plateau and eastern ridges did not allow for vast accumulation of ice. The ice was fairly thin on the central plateau and it moved sluggishly over the flattish-bedrock surface beneath it. Relatively thin glacial accumulations can be inferred because (1) much of the plateau is exposed bedrock, (2) glacial drift is very thin, (3) the greatest depth of any lake (Upper Twin) is only 18 m (60 ft) whereas most are less than 6 m (20 ft), and (4) the Wisconsin regional snowline was about 150 m (500 ft) higher than the general elevation of the northern central plateau.

Williams (1932, p. 384), apparently drawing on his intuition and experience, thought "the whole of the central plateau was covered...by not more than a few hundred feet of ice." He seems to have been correct. Noting that ponded middle Tioga age ice rose to about 2,135 m (7,000 ft) on Prospect Peak and 2,075 m (6,800 ft) on Badger Mountain, and using an ice cap

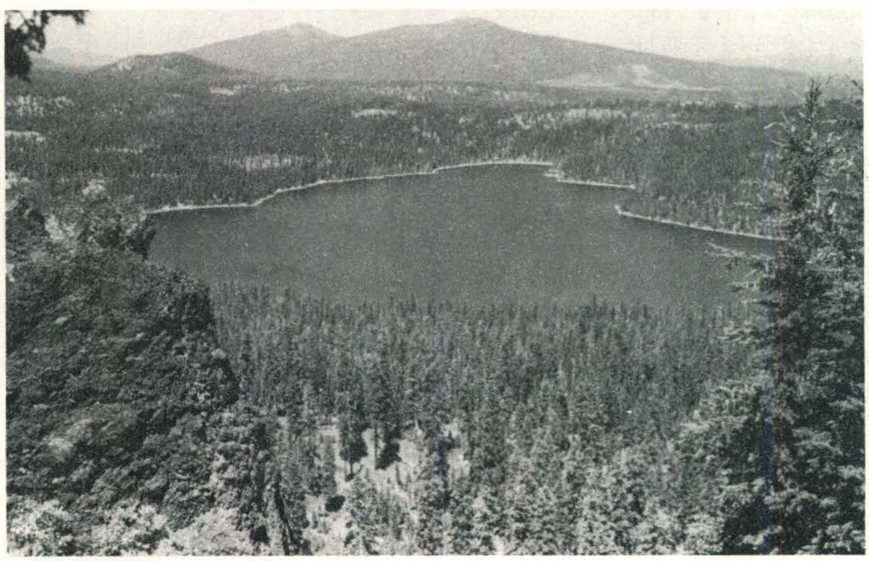

Photo 5. Juniper Lake, view north from Mount Harkness toward Prospect Peak. The lake, about 2.1 km (1.3 mi) wide, is the deepest natural lake in the Park area (72 m, 235 ft), and appears to be more of a constructional depression than an erosional basin. The present outlet is to the west (left) into Warner Valley. During the middle Tioga glaciation this basin was a small local ice field that fed its accumulation to both Warner Valley and to Benner Creek.

Photo 6. Roadcut exposing early Tioga age till in the North Fork of Bailey Creek (Blue Lake Canyon). Oxidation rinds on dense volcanic cobbles in Lassen Park tills range from means of 1.77 mm for pre-Tahoe age to 0.49 mm for middle Tioga age. Respective ranges in other till characteristics include: soil color, from 7.5 YR 4 to 10 YR 3;* depth of oxidation, from at least 3 m (10 ft) to 0.3 m (1 ft); and percentage of soil fines (less than 0.25 mm) from a depth of 0.5 m (20 in), 63.8% to 53.4%. * Munsell colors

surface slope of 19 m per kilometer (100 ft per mile), ice depths of approximately 60 m (200 ft) can be estimated for the plateau surfaces east of Hat Mountain and Crater Butte. Bordering this plateau ice, Lassen Park's shield volcanoes and the Caribou Wilderness area accumulated somewhat greater volumes of glacier ice, but not nearly as much as the Mount Tehama area.

For all of these central and eastern Park areas, the main geomorphic expression of glacial erosion was the scouring out of numerous small shallow basins and the deepening of topographic lows that were mostly along geologic contacts and already a part of the preglacial volcanic landscape. These deeper topographic lows now hold most of the lakes in the park area, including the largest lakes such as Juniper (photo 5), Horseshoe, Butte, and Cluster Lakes.

Depositional Glacial Landforms

A great deal of the material entrained and eroded by ice in the Lassen Park area was eventually deposited as till (photo 6). Ground moraine of middle Tioga age veneers much of the surface area, especially on the relatively level central plateau, in the Caribou Wilderness, and around the cirques and lakes (photo 7). Ridges of till in the form of lateral and recessional moraines (photo 8) accentuate the glacial drift in many places, although these moraines lie predominantly beyond Lassen Park boundaries because most of the "outlet glaciers" reached down to elevations as low as 1,800 m (6,000 ft) (table 2 and figure 1).

The best preserved morainal ridges at these lower elevations outside the park are along Bailey Creek, in the Battle Creek Meadow drainage, and in the southern Caribou Wilderness-Benner Creek region. Within the higher altitudes of Lassen Park area, recessional lateral moraines of significant sizes are rarer, probably because by the time the ice caps had shrunk to "only Park size," they consisted largely of near-stagnant ice masses with smaller, more precarious glacial budgets. This would have induced oscillatory ice-front behavior and the favored deposition of only small recessionals and general ground moraine. Recessional moraines can be seen, however, at a few sites within Lassen Park such as in the area sweeping northeast from Reading Peak and enclosing Summit Lake, and in Cameron Meadow south of Mount Hoffman (photo 9).

Photo 7. Roadcut in Manzanita Creek basin showing two ages of till. The exposure is about 3.6 m (12 ft) high and, from top to bottom, shows 0.9 m (3 ft) of Tahoe till; 0.6 m (2 ft) of pumice (with charcoal dated as "older than 32,000 years"); 0.5 m (1.5 ft) of dark-gray lithic sand; 0.6 m (2 ft) of light colored sand; and 1.0 m (3.5 ft) of pre-Tahoe till. The roadcut is located on Forest Service Road 31N17, 0.16 km (0.10 mi) south of Highway 44.

Over 550 lakes can be found in the Lassen Park-Caribou Wilderness region. Many are small and seasonal. All but about twenty of these lakes are of glacial origin, and all but one of these numerous glacial lakes lie within the limits of middle Tioga till. The exception noted is Dry Lake, a closed depression in the Tahoe-age terminal moraine area of Panther Creek. From this distribution it can be assumed that small till-depression lakes in the Lassen Park area have lifespans of 30,000 to 45,000 years.

SUMMARY

Five ages of glacial till have been identified and differentiated in the Lassen Park area on the basis of time-dependent criteria that included thicknesses of weathering rinds on till stones, soil colors, depths of oxidation, and particle-size distributions of sands. These tills, from oldest to youngest, are informally named pre-Tahoe, Tahoe, early Tioga, middle Tioga, and late Tioga. Pre-Tahoe deposits occur as scattered patches in the western Lassen Park area. Early Tioga is identified in four widely separated valleys, and late Tioga

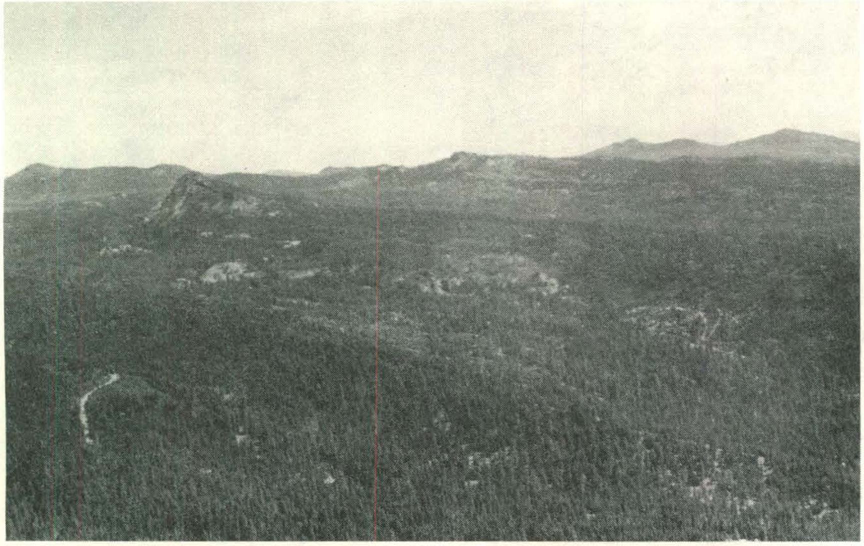

Photo 8. Aerial view northeast across Benner Creek basin. Bonte Peak (elevation 2,372 m; 7777 ft) is left of center, and the eastern ridges are in the background. The crests of prominent middle Tioga moraines slope to the south at a gradient of 85 m per kilometer (445 ft per mile).

till occurs as cirque moraines on the higher mountains in the western part of the area.

Tahoe glaciers covered an estimated 1,010 sq km (390 sq mi), and middle Tioga glaciers covered about 680 sq km (262 sq mi). Both of these advances spread in a generally radial pattern from east-west elongated ice caps centered over the area.

Middle Tioga ice depth on the central plateau was not more than about a hundred meters, but in the valleys of Bailey Creek, Mill Creek, and Warner Creek, glacier lobes exceeded depths of 430 m (1,400 ft). The Wisconsin (Tahoe and middle Tioga) regional snowline was at about 2,300 m (7,500 ft) elevation in the western area, based on cirque floor elevations and the elevations of unglaciated peaks. The snowline rose northeast at a gradient of approximately 12 m per kilometer (65 ft per mile).

The late Tioga regional snowline was about 365 m (1,200 ft) higher than this Wisconsin "ice cap" snowline. Even though amounts of glacial erosion are difficult to infer, some localities in Bailey Creek and Mill Creek indicate 185-275 m (600-900 ft) of valley deepening due to Pleistocene glaciation. In addition, at least one hundred meters of bedrock appear to have been stripped by glaciers from the upper flanks of the Pleistocene composite volcano, Mount Tehama (figures 2 and 5).

Lassen Peak supported glaciers only during late Tioga time. On Eagle Peak small fault scarps caused by the volcanism that created Lassen Peak were only lightly polished by middle Tioga age ice. Glacial striations of middle Tioga age between Eagle and Lassen Peaks are concentric to Lassen Peak, and thus were not caused by glaciers extending from its slopes. This evidence substantiates the conclusion of Crandell and Mullineaux (1970) that Lassen Peak was emplaced at the end of middle Tioga time, about 11,000 years ago.

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Photo 9. View from Inspiration Point (north of Juniper Lake) north over the ridge and swale recessional morainal deposits of middle Tioga age in Cameron Meadow.

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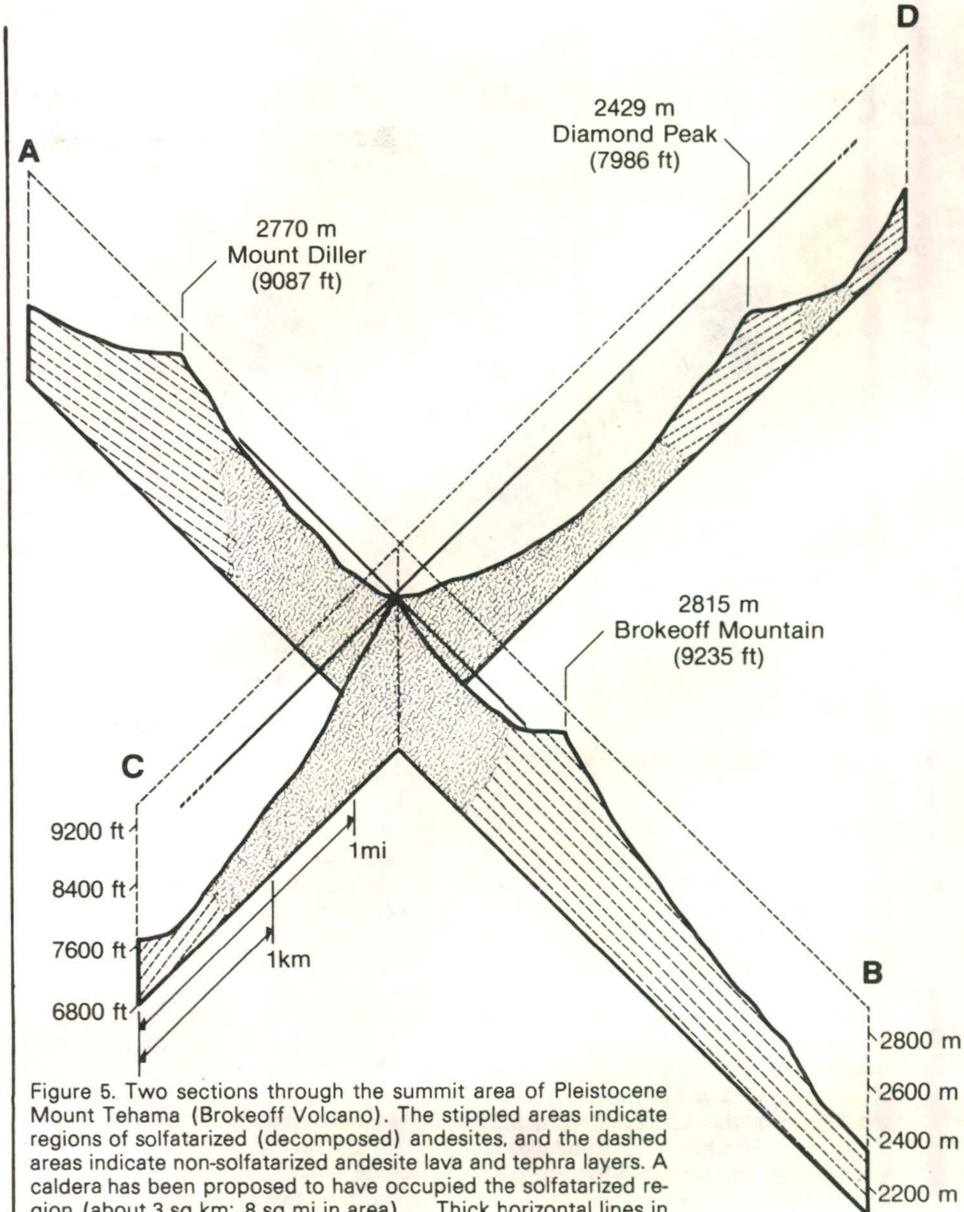

Figure 5. Two sections through the summit area of Pleistocene Mount Tehama (Brokeoff Volcano). The stippled areas indicate regions of solfatarized (decomposed) andesites, and the dashed areas indicate non-solfatarized andesite lava and tephra layers. A caldera has been proposed to have occupied the solfatarized region (about 3 sq km; 8 sq mi in area). Thick horizontal lines in both sections through the common knoll define the inferred floor of the caldera; the area of material now missing from beneath these lines may represent the minimum volume removed by glacial and fluvial erosion. See figure 2; photos 3 and 4.

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CALIFORNIA GEOLOGY

35¢

MAY 1982

CALIFORNIA DIVISION OF MINES & GEOLOGY
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IN THIS ISSUE

Cover: Aerial view north over Emerald Lake (left) and Lake Helen (right) in Lassen Volcanic National Park. The Pleistocene plug-domes of Ski Heil (left) and Eagle Peak (center) rise from behind Emerald Lake; the massive plug-dome of Lassen Peak, emplaced at the very end of Pleistocene time, towers above Lake Helen. Although Lassen Peak was only slightly affected by glaciation, most of the other landforms and landscapes in Lassen Volcanic National Park were greatly modified by the growth and retreat of several Pleistocene ice caps. An article on glaciation in the Lassen Park area begins on p. 95. *Photo by Phillip Kane.*

LAND RECLAMATION FORUM

Shaping Land for Tomorrow: A Land Reclamation Forum will be held October 24-27, 1982, at Michigan State University, East Lansing, Michigan. Industry, government, and design professionals will discuss:

- creative approaches to mining in our environment,
- how reclamation programs are developed,
- experiences in improving community relations, and
- land development opportunities.

For additional information contact: Anthony M. Bauer, School of Urban Planning and Landscape Architecture, Michigan State University, East Lansing, MI 48824; (517) 353-9362.

GALAPAGOS-ECUADOR TRIP

Cosumnes River College Department of Geology and Geological Technology (Sacramento) is offering an 18-day trip to the Galapagos Islands, the Andes Mountains, and the Amazonian rainforest, June 15-July 3, 1982. Travelers will experience a hike up a live volcano, a swim with fur seals, and snorkeling among brightly-colored fish (the Galapagos). The group will travel to the lofty, still-rising Andes and study the geology of the Interandean Graben, a valley formed by fault movements and bordered on both sides by snow-covered stratovolcanoes. Lastly, a trip by motorized dugout through a tropical rainforest is planned—to meet the native Indian peoples in rural areas and to observe their lifestyles, cultures, and crafts. An optional extension to Machu Picchu (Peru) is offered.

For information contact: Dr. Gail Wiggett or Mr. Merwin Rose, Department of Geology and Geological Technology, Cosumnes River College, 8401 Center Parkway, Sacramento, CA 95823, (916) 421-1000, Ext. 217 or 212.