Jour. Research U.S. Geol. Survey
Vol. 2, No. 1, Jan.-Feb. 1974, p. 49—59

CHAOS CRAGS ERUPTIONS AND ROCKFALL-AVALANCHES, LASSEN VOLCANIC NATIONAL PARK, CALIFORNIA

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Abstract.—The Chaos Crags are a group of dacite domes which lie just north of Lassen Peak in northern California. Extrusion of the domes was preceded by pyroclastic volcanism at the same eruptive center which produced pumiceous tephra and hot pyroclastic flows, some of which traveled as far as 8 km. Radiocarbon dates on charcoal from the pyroclastic-flow deposits range from about 1,000 to 1,200 yr. Four or more domes were then erupted which have an estimated combined volume of about 1 km^3. About 300 yr ago, three or more rockfalls from the domes caused high-velocity, air-cushioned avalanches of rock debris which traveled as far as 4.3 km. Pyroclastic flows are regarded as a potential hazard if future volcanic activity occurs in the Chaos Crags-Lassen Peak area. Large rockfall-avalanches from the steep sides of the Chaos Crags might be triggered by a volcanic explosion, by a severe earthquake, or by the eruption of another dome. Either a pyroclastic flow or a rockfall-avalanche could endanger persons and property in the Manzanita Lake area, which is only 2 km from the base of the Chaos Crags and is the most heavily used part of Lassen Volcanic National Park.

The Chaos Crags eruptive center lies just north of the base of Lassen Peak in north-central California (fig. 1). During an assessment of potential geologic hazards in Lassen Volcanic National Park we concluded that some of the most catastrophic geologic events of the recent past resulted directly or indirectly from volcanism at the site of the Chaos Crags. In brief, the Chaos Crags eruptive episode began with explosive eruptions of dacite pumice, some of which resulted in hot pyroclastic flows; these were followed by the extrusion of dacite domes to form the Chaos Crags. Much later, parts of the domes collapsed and caused avalanches of rock debris which traveled as far as 4.3 km and created the Chaos Jumbles (fig. 1). Both the hot pyroclastic flows and the avalanches covered parts of an area that is now occupied by various facilities at the park's Manzanita Lake visitor center.

Williams (1928, 1932) described the pyroclastic eruptive activity at the site of the Chaos Crags as well as the eruption of the domes and the subsequent rockfall-avalanches. He believed that the volcanism and the avalanches occurred within a short time span about 200 yr ago (Williams, 1932, p. 350, 359). From a subsequent study of the avalanche deposits, however, Heath (1960, 1967) concluded that rockfall-avalanches had occurred at three widely separated times between about 1,500 and 300 yr ago. Macdonald (1963, 1964) mapped the geology of the Manzanita Lake and Prospect Peak quadrangles, in which the Chaos Crags lie, and recognized the presence of pyroclastic-flow deposits.

In the course of our study we found that the Chaos Crags eruptive episode occurred between about 1,000 and 1,200 yr ago and included pyroclastic eruptions separated by intervals of as much as several decades. We also concluded that the Chaos Jumbles were formed by three or more high-speed air-cushioned avalanches, all of which occurred about 300 yr ago. The following discussion describes the evidence on which these conclusions are based, summarizes our view of the sequence of geologic events in the Chaos Crags area, and points out the potential hazards if similar events occur in that area in the future.

The terms "pyroclastic-flow deposit" and "tephra" are defined here because these terms have been used previously in a different sense, or because the events or deposits they describe have had other names applied to them by other workers. We will use the term "pyroclastic-flow deposit" to describe the deposit of a hot dry flow of volcanic rock debris that is propelled chiefly or wholly by gravity and lubricated by air trapped and heated within the debris, or by hot gases emitted by the rock debris, or by both. The deposits described here as tephra originated as fragmental material that was erupted high into the air and then carried laterally either by the force of the eruption or by wind as the material fell back to the land surface.

The 1914—17 volcanic activity at Lassen Peak, which included the eruption of tephra and lava, the formation of lahars, and a hot lateral blast of great force, has been described by Day and Allen (1925), Williams (1932), and others. Although future volcanism of these kinds would surely endanger life and property, the volcanic history and potential hazards of Lassen Peak are not described in this report.

DEPOSITS FORMED DURING THE CHAOS CRAGS ERUPTIVE EPISODE

The Chaos Crags eruptive episode began with eruptions of dacite pumice and nonvesicular rock fragments from vents that are now covered by the Chaos Crags domes. The resulting sequence of tephra deposits in the area adjacent to the south side of the Chaos Crags includes alternating beds of ash, lapilli, and blocks. The upper part of the sequence may include a few fine-grained pyroclastic-flow deposits, and the sequence is overlain by such a deposit which contains moderately vesicular blocks of dacite as large as 2.5 m across. Most of the tephra deposits consist of white pumiceous rock in which the only abundant Fe-Mg minerals are hornblende and biotite. Orthopyroxene, clinopyroxene, and olivine are sparse in some rock fragments and absent in others.

The tephra deposits are more than 2 m thick in the area between the base of Lassen Peak and the Chaos Crags. To the east they gradually thin to 0.3–0.6 m at a distance of 3–5 km. In the Butte Lake area, about 19 km northeast of the Chaos Crags, the tephra deposits are about 1 cm thick. To the west they thin more abruptly, and are barely recognizable beyond the boundary of Lassen Volcanic National Park 4 km west of the Chaos Crags.

Close to the vents some showers of pumice were hot enough to char vegetation. One such shower which fell to the southwest is represented by a charcoal-bearing pumice deposit as much as 15 cm thick on the west flank of Loomis Peak, 4 km from the Chaos Crags. Charcoal was also found in tephra deposits at several places directly south of the Chaos Crags, and about 3 km southeast of the Chaos Crags in the northwestern part of the Devastated Area.

The eruptions that formed these deposits did not all occur in quick succession. At one place small trees that had taken root in one tephra layer had grown for more than a decade and had reached a height of nearly a meter before they were buried and converted to charcoal by a subsequent fall of hot pumice. Although an exact timespan cannot be assigned to the intervals between pyroclastic eruptions, it may have taken as much as several decades for conifer seedlings to become established on a newly erupted tephra deposit.

Pyroclastic-flow deposits

During the Chaos Crags eruptive episode pyroclastic flows of hot pumice repeatedly moved from the vent areas downslope into the valleys of Manzanita and Lost Creeks. Williams (1928, p. 243) included both the tephra and the pyroclastic-flow deposits in his description of a "thick mantle of tuff, carrying plentiful lapilli and 'bread-crust' bombs of a hornblende dacite, [which] covers the slope which descends from the base of the crags onto the broad plateau west of Manzanita Lake." Macdonald (1963) differentiated the tephra deposits from the "ash flow of Manzanita Creek." He (Macdonald, 1964) also collected charcoal from a possible "glowing avalanche" deposit along Lost Creek, but did not map pyroclastic-flow deposits in the Lost Creek valley.

The pyroclastic-flow deposits are loose unsorted mixtures of breadcrusted blocks and lapilli of dacite pumice in a matrix of sand-sized pumice; angular lapilli of nonvesicular glass are common. The deposits of individual pyroclastic flows are generally 1–4.5 m thick. The multiple nature of the deposits is shown by exposures in the bank of Manzanita Creek 0.7 km east of Manzanita Lake, where four pyroclastic-flow deposits can be seen superposed (measured section 1).

Measured section 1

[Location: NW¼SW¼ sec. 17, T. 31 N., R. 4 E.]

		Meters
9.	Sand and gravel, stratified, consisting of pumice and nonvesicular rock; some beds are white to very pale brown well-sorted medium sand; breadcrusted blocks of pumice on surface of deposit probably were emplaced by a later pyroclastic flow	1.0
8.	Pyroclastic-flow deposit: unstratified and poorly sorted mixture of white ash- and lapilli-sized pumice and nonvesicular rock fragments; upper 0.3 m is light reddish brown	> 1.5
Covered interval		3.3
7.	Sand and gravel, white, contains scattered angular fragments of pumice and nonvesicular rock, horizontally stratified.	> 1.5
6.	Pyroclastic-flow deposit: unstratified and unsorted mixture of pumice and nonvesicular rock fragments as large as 1.5 m in diameter in matrix of white fine to coarse ash, faint pinkish-gray cast in upper 1 m	1.2
5.	Pyroclastic-flow deposit: unstratified and poorly sorted mixture of pumice and nonvesicular rock fragments mostly less than 15 cm in diameter in white ash matrix, contains abundant charcoal (radiocarbon sample W-2137, 1,120±300 yr)	1.0
4.	Silt and fine to medium sand, pinkish-gray; contains scattered fragments of pumice and nonvesicular rock which are mostly less than 2 cm in diameter	0.3–0.5
3.	Pyroclastic-flow deposit(s): medium to coarse white ash mixed with lapilli of nonvesicular rock and breadcrusted blocks of pumice, contains charcoal (radiocarbon sample W-2135: 1,230±300 yr), zone 1.8–2.4 m above base is faintly bedded and may represent a contact between two pyroclastic-flow deposits	3.6
2.	Fine to very fine sand, grayish-brown, horizontally bedded	0.03
1.	Glacial drift: boulders of nonvesicular dacite in matrix of fine to medium sand, oxidized yellowish brown	> 1.0

Charcoal samples from the two lowest pyroclastic-flow deposits along Manzanita Creek had radiocarbon ages of 1,230±300 (W-2135) and 1,120±300 (W-2137) yr. Trees more than 325 yr old grow on top of the youngest pyroclastic-flow deposits at this locality. No evidence was found within the sequence of a time interval between successive pyroclastic flows, and we infer that they all were formed during a single, though intermittent, eruptive episode between about 1,200 and 1,000 yr ago. In a review of volcanism in northern California, Macdonald (1966) reported a radiocarbon date of less than 200 yr (W-812; see Rubin and Alexander, 1960, p. 156) for charcoal from a "glowing avalanche" deposit in the vicinity of Manzanita Lake, and noted that the avalanche "appears to have come from Lassen Peak but may have occurred about the time of the last eruption of the Chaos Crags."

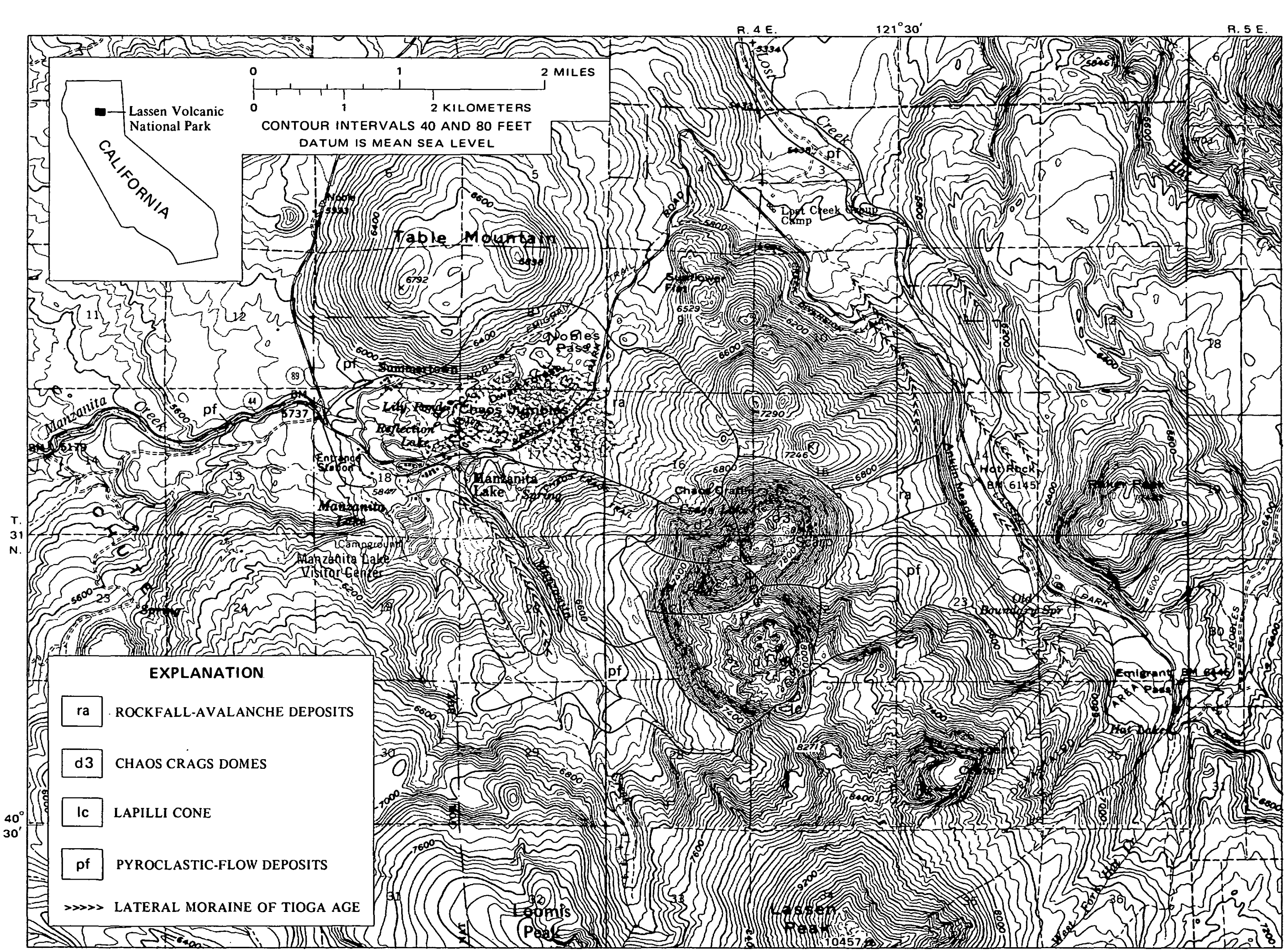

Figure 1.—Map of the northwestern part of Lassen Volcanic National Park, showing distribution of geologic units described in text. Subdivisions of the Chaos Crags domes also are discussed in text.

The significance of the date reported by Macdonald is not known, but our radiocarbon dates and tree-ring data indicate that it does not apply to the pyroclastic-flow deposits discussed here.

The interpretation of units 3, 5, 6, and 8 in measured section 1 as pyroclastic-flow deposits is based on the abundance of pumice in them, poor size-sorting, and on evidence that the deposits were emplaced at a high temperature. This evidence includes the facts that all the wood observed in those units has been converted to charcoal, and that pinkish-gray oxidized zones are present at the tops of some of the deposits. In addition, examination of rock fragments from some of the deposits with a fluxgate magnetometer showed a preferred orientation of remanent magnetism (fig. 2); thus, ferromagnetic minerals in the rock fragments were still above their Curie temperatures (probably at least several hundred degrees C) when the deposits came to rest (Aramaki and Akimoto, 1957; Crandell, 1971, p. 5). Similar deposits at the present ground surface show digitate margins and other features that suggest an origin by flowage.

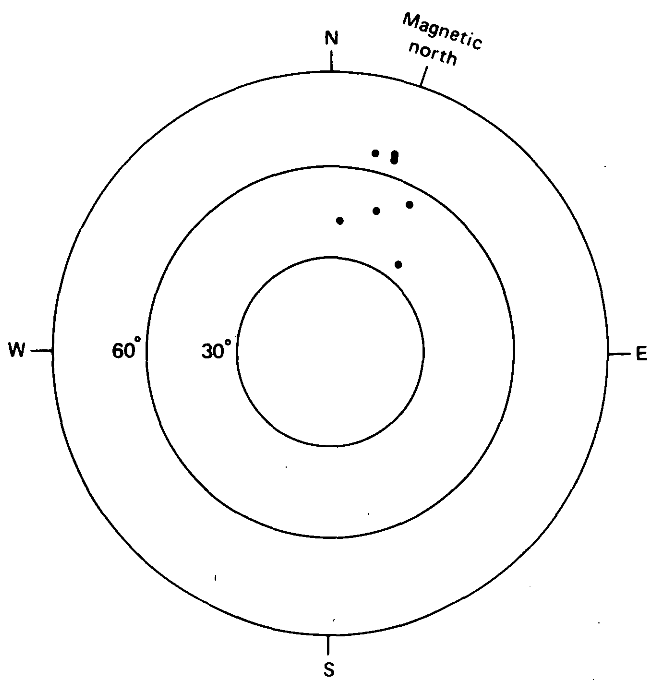

Figure 2.— Point diagram of azimuth and dip of north-seeking poles in pumice fragments from a pyroclastic-flow deposit (unit 3, measured section 1).

Breadcrusted blocks of pumice are so abundant at the surface of some pyroclastic flows that they form a virtual "pavement" (fig. 3). The exposed dimensions of some of these blocks are as much as 2 by 2.5 m, and blocks 0.5 m in diameter are common. Just west of Manzanita Creek, in an area 2.5 km southeast of Manzanita Lake, a pyroclastic-flow deposit that forms the ground surface probably is not more than 2 m thick, but blocks as large as 1.2 by 1.5 by 1.5 m are present at its surface.

The lateral margin of the pyroclastic-flow deposit that forms the ground surface west of Manzanita Creek is digitate; one lobe along the margin is about 15 m long and 5–6 m wide, and another is 8 m long and 2–3 m wide. These lobes stand about 0.5 m higher than the preexisting surface beyond them. Elsewhere the margin of the deposit is somewhat higher than the main body of the deposit and resembles a levee typically formed by a mudflow. Although these marginal features suggest formation by a lahar, remanent magnetism of blocks in one of the lobes indicates that the deposit was emplaced as a hot pyroclastic flow.

The pyroclastic flows that moved westward into the Manzanita Creek drainage seem to have come from at least two vent areas, one at the south end and the other at the north end of the site of the Chaos Crags. The flows originating at the southern vent area followed two principal routes. Some moved northwestward down the Manzanita Creek valley and were channeled by a lateral moraine. At the northern end of the moraine, 0.6 km east of Manzanita Lake, the flows spread out and covered much of the low area east and northeast of the lake. The sequence of deposits in measured section 1 indicates that at least four pyroclastic flows followed this route. Other flows moved directly westward from the southern vent area across the head of Manzanita Creek and extended down a valley parallel to and 0.5 km west of Manzanita Creek, terminating near the southeast edge of the site of Manzanita Lake campground.

The pyroclastic flows originating at the northern vent area moved west along the area now covered by the Chaos Jumbles, and one flow reached nearly 4 km west of the park down the Manzanita Creek valley. The deposit of this pyroclastic flow crops out in roadcuts along State Highway 44, and it is especially well exposed in a roadcut at the junction of Highways 44 and 89 (fig. 4), where it is 1–2 m thick and consists of blocks of breadcrusted pumice in a white ash matrix. It overlies a soil profile developed on a pyroclastic-flow deposit that is more than 32,000 yr old (radiocarbon sample W-2259; Crandell, 1972, p. C182). Abundant charcoal and the preferred orientation of magnetic poles in the pumice blocks indicate that the upper pyroclastic-flow deposit was hot when it came to rest.

Pyroclastic-flow deposits from vents now hidden by the Chaos Crags form a fill terrace in the Lost Creek valley and blanket much of the west valley wall between the base of the Crags and the valley floor upstream from the Lassen Park Road bridge in sec. 14. Four pyroclastic-flow deposits in the valley are well exposed in the west bank of Lost Creek just downstream from the bridge (measured section 2). Pumice blocks from units 4 and 9 of the sequence described here have a preferred magnetic orientation; thus, the deposits were hot

Figure 3.—Ground surface west of the Chaos Crags is made up of a pavement of breadcrusted pumice blocks deposited by hot pyroclastic flows (see text).

when they were emplaced. Macdonald (Rubin and Alexander, 1960, p. 155) collected charcoal from this locality which had a radiocarbon age of 1,320±200 yr (W-758), but the stratigraphic horizon from which the sample was collected is uncertain. A sample of charcoal collected by us for radiocarbon dating from the lowest pyroclastic-flow deposit exposed (unit 4 of measured section 2) had an age of 1,010±250 yr (W-2261). The deposits here are thus about the same age as those in the area west of the Chaos Crags.

Measured section 2

[Location: NE¼NW¼ sec. 14, T. 31 N., R. 4 E.]

		Meters
10.	Tephra: mixture of pumice and nonvesicular rock fragments as large as 5 cm in diameter in a loose ash matrix	0.09
9.	Pyroclastic-flow deposit: pumice blocks as large as 0.3 m and nonvesicular glassy rock fragments 1–6 cm in diameter in a white ash matrix; deposit has a pinkish-gray cast in upper 1.5–1.8 m and contains charcoal; layer of forest duff 5–7 cm thick at top	4.5
8.	Pyroclastic-flow deposit: pumice and nonvesicular rock fragments as large as 7 cm in diameter in a white ash matrix; upper contact is gradational	0.3
7.	Sand and granule gravel, horizontally bedded	0.15
6.	Pyroclastic-flow deposit; pumice blocks in a light-gray to white ash matrix	1.8
5.	Silt and fine sand, pinkish-gray; lower contact is sharp but upper contact is gradational	0.27
4.	Pyroclastic-flow deposit: weakly breadcrusted pumice blocks in a light-gray to white ash matrix, contains charcoal (radiocarbon sample W-2261: 1,010±250 yr)	1.0
3.	Sand and granule to pebble gravel, consists chiefly of white pumice, locally has lenses of white sand at top	1.0
2.	Peat and peaty silt (radiocarbon sample W-2232 from top 0.75 cm: 4,600±600 yr; radiocarbon sample W-2231 from bottom 0.75 cm: 5,400±600 yr)	1.0
1.	Sand and pebble to cobble gravel, consists mostly of gray and reddish-gray dacite	>0.7

Figure 4.—Charcoal-bearing pyroclastic-flow deposit overlying an older, weathered pyroclastic-flow deposit in a roadcut near the west edge of Lassen Volcanic National Park (see text).

Pumice deposits on the west valley wall west of the line between secs. 23 and 24 were formed mostly by pyroclastic flows, but those east of that line seem to be wholly tephra. The tephra deposits do not include the breadcrusted pumice blocks that characterize the pyroclastic-flow deposits. Some of the hot pyroclastic flows continued down the Lost Creek valley beyond the north edge of sec. 3.

At least one pyroclastic flow extended up onto the east valley wall of Lost Creek directly east of the highway bridge in sec. 14. The highest flow deposit is about 38 m above the valley floor. If resistance due to friction is not considered, this flow must have been moving at least 100 km/h (60 mi/h) across the valley floor, in order to have reached so high on the valley wall. The pyroclastic flow probably originated at a vent about 2.4 km to the southwest, at an altitude of at least 2,120 m (7,000 ft), and acquired high velocity as it flowed downward through a vertical distance of nearly 330 m to the floor of the Lost Creek valley.

Chaos Crags domes

The dacite domes that form the Chaos Crags cover an area of about 5 km^2 and rise 300–450 m above their base which is at an altitude of about 2,120 m (fig. 5). The Crags include two main "protrusions" (Williams, 1928, p. 245–249). The southern protrusion is a roughly circular dome (labeled d1 on fig. 1) about 1.7 km in maximum diameter. Its southern edge has disrupted a small lapilli cone about 400 m in diameter. The northern protrusion of Williams consists of a cluster of three domes (labeled d2, d3, d4, on fig. 1). Dome 2, on the northwest side of the cluster, was mostly removed by the great rockfalls which formed the Chaos Jumbles. To the east, dome 3 consists of two parts—a high mass on the southwest is separated from a lower northeast mass by an arcuate scarp; this lower mass may actually be another dome.

Areas of hydrothermally altered rock locally stain the Chaos Crags and are especially abundant on domes 2 and 3. The alteration probably occurred mostly during the eruption and cooling of the domes, but large volumes of steam and other gases were reported to be issuing from dome 4 as recently as 1857 (Williams, 1932, p. 347).

The surfaces of all the domes are extremely rough and consist of "a chaotic assemblage of gigantic, loose, angular blocks" (Williams, 1928, p. 246). Williams inferred that the lava which formed the domes moved dominantly upward and that the dacite was too stiff to move far laterally. However, flow banding with a low inward dip indicates some lateral flow near the southern margin of the southern dome (Williams, 1928, p. 245–246), and the westward extension of this dome down across a topographic scarp suggests more than 350 m of lateral movement there.

The volume of the domes seems to be approximately equal to the volume of the tephra and pyroclastic-flow deposits. If it is assumed that the domes have an average thickness of 200 m, their total volume is 1 km^3. The total volume of all the fragmental material probably does not exceed 1 km^3.

There is no direct evidence of the age of the Chaos Crags domes, except that they postdate the pyroclastic-flow deposits which are between about 1,000 and 1,200 yr old. By analogy with similar eruptive sequences which have been observed, Williams (1932, p. 350) suggested that the time interval between the tephra eruptions and the later eruption of a dome from the same vent may not have been more than a few weeks or months. It is not known, however, whether all the domes were erupted at the same time. The charcoal remains of small trees rooted in one tephra layer and buried by another show that perhaps several decades elapsed between tephra eruptions. This, as well as the range of radiocarbon dates, suggests that the various eruptive events which produced tephra, pyroclastic flows, and domes may have been separated by several quiescent intervals.

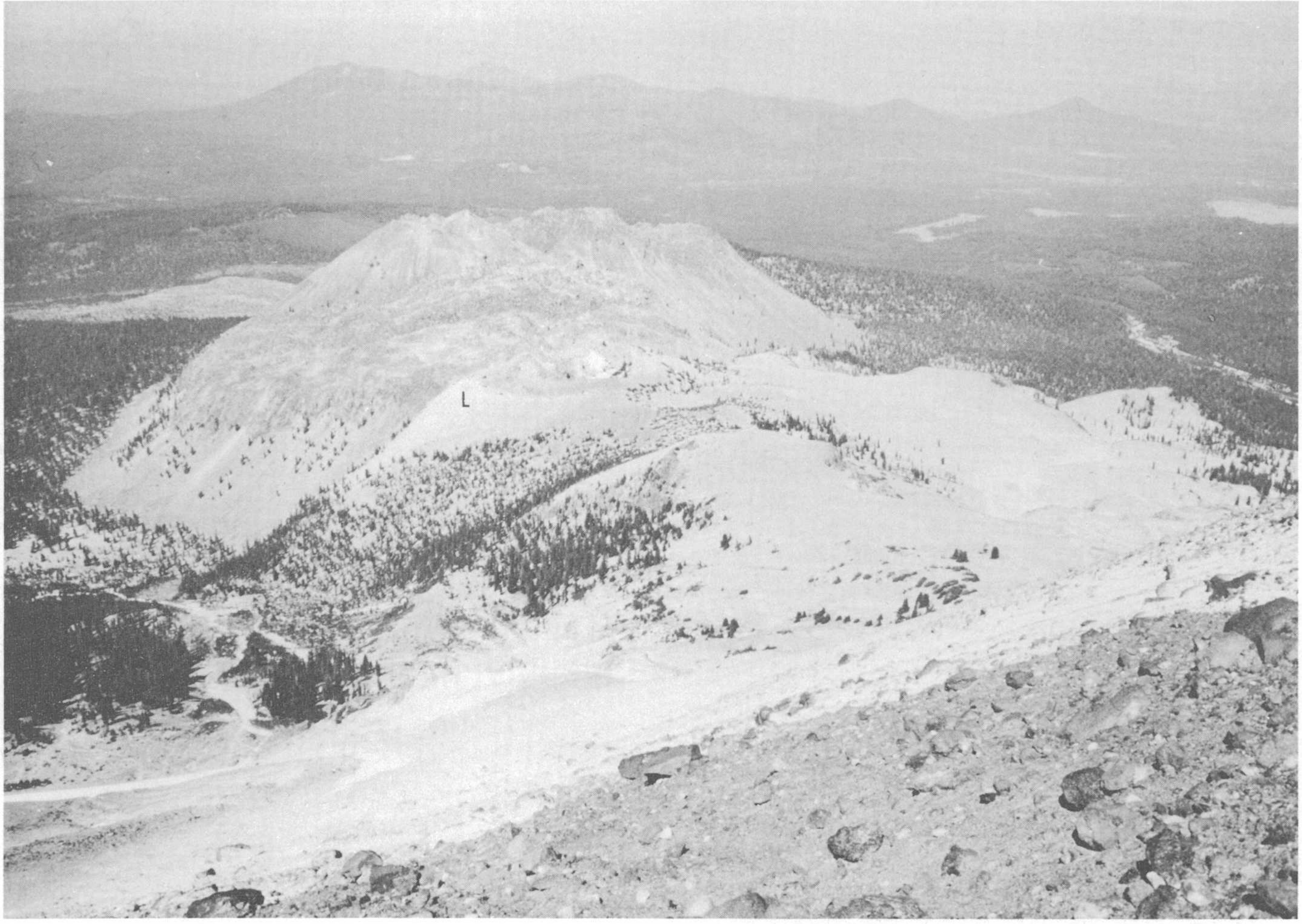

Figure 5.—View from the top of Lassen Peak northward across the Chaos Crags. Light-colored deposits at right center are tephra that probably was mostly erupted from a vent situated at the small lapilli cone (L) at the south margin of the Chaos Crags domes.

CHAOS JUMBLES ROCKFALL-AVALANCHE DEPOSITS

The Chaos Jumbles is a broad band of angular rock debris which extends from the northwest base of the Chaos Crags northwestward and westward for a distance of about 4.3 km and covers an area of nearly 8 km^2 (figs. 1, 6, 7). Individual fragments in the deposit range in diameter from a few millimeters to several meters. The rock debris probably is as much as 40 m thick in its central part. Williams (1928, p. 252) estimated the volume of the debris to be at least 150 million yd^3 (about 115 million m^3), and profiles made from the topographic map suggest that the volume may be as much as 150 million m^3.

Surface features of the Chaos Jumbles include ridges and furrows of rock debris, marginal ridges, steep and abrupt margins, and conical and domelike mounds. Transverse ridges and furrows have wavelengths of about 10 m to 100 m or more; some of these can be traced across at least half the width of a single avalanche deposit. There are, in addition, longitudinal ridges, scarps, and furrows, some of which are more than 1 km long. Where longitudinal and transverse surface features intersect, they typically cross one another without being offset. Reflection Lake and some nearby shallow ponds occupy shallow longitudinal depressions within the avalanche deposits. The surface of the western half of the deposits slopes westward about 60 m/km.

Rock fragments in the Chaos Jumbles are fresh and unaffected by weathering; however, some masses of hydrothermally altered rock form strips a few meters wide and a hundred meters or more long in the deposits between the Lassen Park Road and the base of the Chaos Crags. These strips trend parallel to the long axis of the avalanche deposits and probably resulted from the progressive disaggregation of altered rock masses during transport. Their continuity and restricted distribution suggest an absence of turbulence within the moving avalanche.

The avalanche debris extends up the south slope of Table Mountain to a point that is about 121 m higher than the base

Figure 6.—View from the top of the rockfall scarp on the Chaos Crags westward across the Chaos Jumbles toward Manzanita Lake. Dashed line shows extent of the avalanche deposits. Arrows point to areas of hydrothermally altered rock debris.

of the mountain at Nobles Pass (fig. 1). If it is assumed that as the avalanche reached its highest point its kinetic energy was wholly converted to potential energy, and that no energy had been expended in overcoming frictional resistance, the avalanche must have had a speed at the foot of Table Mountain of no less than 160 km/h (100 mi/h). It seems certain that the actual speed was somewhat greater because frictional resistance would have developed in the avalanche as it moved up the slope of Table Mountain.

Williams (1928, p. 257; 1932, p. 355–356) regarded the Chaos Jumbles as chiefly the deposit of a rapidly moving dry rock stream or avalanche, but in order to explain the great mobility of the moving mass he suggested that its basal part was wet and moved as a mudflow. He suggested that the avalanche was caused by a massive rockfall from the Chaos Crags which had been triggered by a steam explosion soon after formation of the domes.

The general lack of displacement of the transverse and longitudinal ridges and furrows of one by the other over much of the central part of the avalanche deposits, together with the distribution of altered rock, suggests that the avalanche was moving as a nonturbulent sheet of rubble just before it came to rest. Such a sheet, moving above the ground surface on a cushion of compressed air, has been proposed as the origin of other avalanche deposits which show evidence of great velocity and a long distance of movement on low slopes (Shreve, 1968, p. 37–44). Shreve has suggested that the transverse ridges and furrows of such air-cushioned avalanches are formed after the leading edge of the avalanche strikes the ground and as the "zone of impact travels like a wave back up the length of the avalanche." The evident velocity and the surface features of the Chaos Jumbles avalanche deposits indicate that they, too, were formed by avalanches traveling on cushions of compressed air.

Heath (1960) postulated that the Chaos Jumbles were formed by at last three avalanches which were separated by intervals of hundreds of years, and he cited both geological and botanical evidence to support the conclusion. He (1967)

Figure 7.—View southeastward from the Lassen Park Road toward the reentrant formed in the Chaos Crags by rockfalls. The high rock mass on the right is the dome that was reported to be emitting steam and other gases in the mid-1800's. Rock debris of the Chaos Jumbles rockfall-avalanche deposits is in the foreground.

referred to a "300-year-old avalanche," dated by the ages of the oldest trees growing on it, a "750-year-old avalanche," and a "1,500-year-old avalanche," but he pointed out that the latter two ages were subjective estimates.

We have reviewed the evidence for age differences within the avalanche deposits because any assessment of the likelihood of future avalanches would be influenced by the knowledge that avalanches had occurred at several widely separated times in the past, rather than at only one time.

The geologic evidence cited by Heath for widely different ages includes, in the oldest avalanche deposit, the presence of fewer sharp-edged fragments, a higher content of interstitial "soil," and greater rounding and flattening of hummocks; all these features were thought to indicate a greater degree of weathering than is present in the other avalanche deposits. In addition, Heath noted the presence of basalt blocks on the northern margin of the oldest avalanche deposit, which he interpreted to have moved from the slope of Table Mountain down across the avalanche deposit by slow downslope transport. Heath (1960, p. 746) believed that such transport must have required "a long period of time."

To reevaluate this evidence, the surface of the avalanche deposits was examined and shallow pits were dug. No consistent difference was found in edge-rounding or in degree of oxidation between the "oldest" and "youngest" avalanche deposits. There is, however, a higher proportion of fine material in places in the "oldest" deposit. But it seems likely that the fine grain size represents the original texture of the deposit in most places because there is no other evidence of subaerial weathering. Elsewhere, the abundance of fine material seems to be related to the altered nature of the parent rock, which permits it to crumble more rapidly than the unaltered rock debris. This alteration evidently took place in the rocks of the Chaos Crags before the rockfalls occurred. Hummocks are relatively rounded where the overall grain size of the deposit is finer, and their shape probably is related to the grain size. Similar variations in texture and topography are present in deposits of several avalanches that originated on the northeast side of Mount Rainier, Wash., in December 1963 (Crandell and Fahnestock, 1965). These avalanches are known to have occurred within a short period of time, perhaps within minutes of each other, and certainly all within a period of not more than 2 mo.

Basalt fragments derived from the side of Table Mountain are present on the north edge of the "oldest" avalanche deposit, as reported by Heath. But these blocks occur on the tops of hummocks and ridges as well as between them, and cannot have reached positions on top of the hummocks by slow downslope transport. Instead, they must have been picked up and carried by the avalanche itself, and are now in virtually the same positions as when the avalanche came to rest.

We believe, therefore, that the geologic evidence does not support the hypothesis that the avalanche deposits are of significantly different ages.

Botanical evidence cited by Heath to show age differences between the "oldest," "middle," and "youngest" avalanche deposits included differences in vegetative cover, size of trees, and proportions of species present. Differences in the character of the vegetation are clear from place to place on the deposits. The central part is sparsely dotted by small trees and is bordered on the north by deposits which locally bear a denser growth of larger trees. Still farther north is a narrow band in which trees are very large at the margin of the deposits. Heath postulated that these size differences, as well as differences in distribution of tree species, represented stages of a forest succession that is dependent on time.

The ages of the trees, however, do not indicate a substantial difference in age from one avalanche deposit to the next. Growth-ring counts by Heath and by us show that the oldest trees on the "oldest," "middle," and "youngest" deposits are about the same age, between 260 and 290 yr old. In contrast, trees much older than 300 yr grow on moraines and pyroclastic-flow deposits that are adjacent to the Chaos Jumbles. General agreement exists that trees should begin to grow soon on newly formed surfaces, depending on the availability of seed, the presence of a seedbed of fine-grained material, and a favorable climate (Division of Timber Management Research, 1965; Lutz, 1956; Sigafoos and Hendricks, 1969). These requirements are met on the "oldest" avalanche deposits which are bordered by forest growing on older deposits. Sigafoos and Hendricks (1969) found that under favorable conditions at Mount Rainier, Wash., trees start to grow about 5 yr after a surface becomes stable.

The lack of evidence of one or more generations of trees older than the ones now standing on the "oldest" avalanche deposit also suggests that the deposit is not older than about 300 yr. An important part of evidence for an older generation of trees in a forest is the existence of fallen logs as large or larger than the standing trees. Large logs are not present on the surface of the "oldest" avalanche, yet they are common on the thousand-year-old pyroclastic-flow deposits adjacent to the Chaos Jumbles. Other botanical evidences such as thickness of humus, size of trees, and species frequency of trees on the various parts of the Jumbles were examined by Sigafoos, who concluded that the evidence as a whole does not support a significant difference in age from one part of the avalanche deposits to another.

Consequently, we believe that the ages of the trees on the "oldest" avalanche deposit closely date it, and that the other parts of the Chaos Jumbles are of practically the same age. It seems likely that the trees on the "oldest" avalanche deposit are larger, more abundant, and represent different proportions of species because of microenvironmental differences such as texture of the deposits, light intensity, and available moisture.

As a further check, a brief study was made in 1972 of lichens on the avalanche deposits adjacent to the Lassen Park Road east and southeast of Nobles Pass (fig. 1). Specimens of two lichen species, *Rhizocarpon geographicum* and *Lecidea atrobrunnea*, were examined because studies elsewhere have shown them to have growth rates slow enough to date deposits many hundreds of years old (for example, Beschel, 1961; Benedict, 1967). Representative examples of these lichens, and others, were collected and subsequently identified by Professor William A. Weber, Department of Biology, University of Colorado. Growth rates have not been determined for lichens in this area, although specimens of *R. geographicum* as large as 15 mm in diameter were found in the Devastated Area on blocks of lava which were erupted by Lassen Peak in 1915. Growth-rate curves for *R. geographicum* and *L. atrobrunnea* in other areas show them to have relatively rapid early growth that is followed by slower growth.

The largest diameters of lichens on northward-facing surfaces of rock fragments were measured on each of the three avalanche deposits, with the results tabulated below. *R. geographicum* was not found on the "youngest" avalanche deposit; specimens of the only Rhizocarpons seen there were identified by Professor Weber as *R. ferax* H. Magn.

Maximum diameters, in millimeters, of lichens found on the Chaos Jumbles avalanche deposits

	"Youngest"	*"Middle"*	*"Oldest"*
R. geographicum	...	52	50
L. atrobrunnea	72	83	79

Although the results of this brief study of lichens are not definitive, the absence of appreciable size differences seems to support the view that the three avalanche deposits are of approximately the same age.

In summary, the Chaos Jumbles probably includes the deposits of three or more avalanches, but we believe that both geological and botanical evidence indicates that they all occurred at about the same time. The age of 300 yr, calculated by Heath for the "youngest" deposit, seems to apply to all of the avalanche deposits.

A rockfall-avalanche deposit that is similar to the Chaos Jumbles deposit, but much smaller, underlies an area east of dome 3 of the Chaos Crags (fig. 1). The age of this deposit is not known. There is no large reentrant in the flank of the dome at its head. It is possible that the arcuate scarp of dome 3, mentioned previously, represents a part of a cliff left by a rockfall, and that the lower mass of this dome is actually a younger dome that was erupted after the rockfall occurred.

POSSIBLE CAUSES OF THE ROCKFALLS

Any one of the several events could have triggered the rockfall-avalanches. Williams (1928, p. 251) suggested that the cause was a series of steam explosions at the northwest base of the Chaos Crags domes. If, as we have suggested, the rockfalls followed one another in quick succession, the first might have been started by a steam explosion and the subsequent falls could have resulted from the collapse of steep, unstable cliffs left by the initial rockfall. Another possibility is that the rockfalls were caused by the collapse of steep cliffs during an earthquake.

Still another cause of the rockfalls could have been the intrusion of a dome into the central part of the Chaos Crags, or renewed movement of one of the existing domes. Although we have no direct evidence of either of these events, the fact that dome 4 (fig. 1) was reported to be emitting steam and other gases constantly during the period 1854–57 (Williams, 1932, p. 347) suggests that this dome is younger than the others. It adjoins the domes in which the rockfalls originated. If a new dome had been erupted into the central part of an older group of domes, it could have caused oversteepened slopes by pushing and tilting the surrounding rocks. If these rocks were already highly fractured and unstable, the oversteepening could have resulted in one or more massive rockfalls.

POTENTIAL VOLCANIC HAZARDS

The kinds of volcanic events that are recorded by deposits adjacent to the Chaos Crags include the fall of hot pumice, hot pyroclastic flows, and rapidly moving rockfall-avalanches, although the latter may not be a direct consequence of volcanic activity. If dacitic volcanism should occur again within or close to the Chaos Crags, a sequence of events similar to those of the Chaos Crags eruptive episode probably would recur, namely the eruption of tephra and pyroclastic flows followed by the extrusion of domes. Such a sequence would almost certainly be preceded by a period of activity on a small, relatively harmless scale. Thus, large-scale eruptions would not threaten human life if adjacent areas had been evacuated as a precautionary measure at the start of the eruption.

Areas that would be directly threatened by pyroclastic flows include the zones immediately downslope from the active vent, and especially valley floors for a distance of at least 15 km from the vent. Tephra erupted in the past has mainly been carried eastward by the wind, and the distribution of tephra deposits from future eruptions would likewise be governed by the direction and strength of winds, as well as by the location of the erupting vent.

A potentially more hazardous event than an eruption would be the formation of another rockfall-avalanche at the Chaos Crags or from the flank of a newly erupted dome. Such an avalanche could be caused by a volcanic explosion during the eruption of the dome, or by an earthquake unrelated to volcanism. A rockfall-avalanche might not be preceded by any warning, and the extremely high velocity would surely preclude evacuation in time to prevent loss of life. Because of this, we regard as hazardous the areas within a distance of about 5 km downslope from the Chaos Crags to the east and to the west. There seems to be no way to warn or protect persons in the path of such an avalanche, and we think that future use of the areas which might be affected should be restricted.

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JOURNAL OF RESEARCH

OF THE U.S. GEOLOGICAL SURVEY

JANUARY–FEBRUARY 1974
VOLUME 2, NUMBER 1

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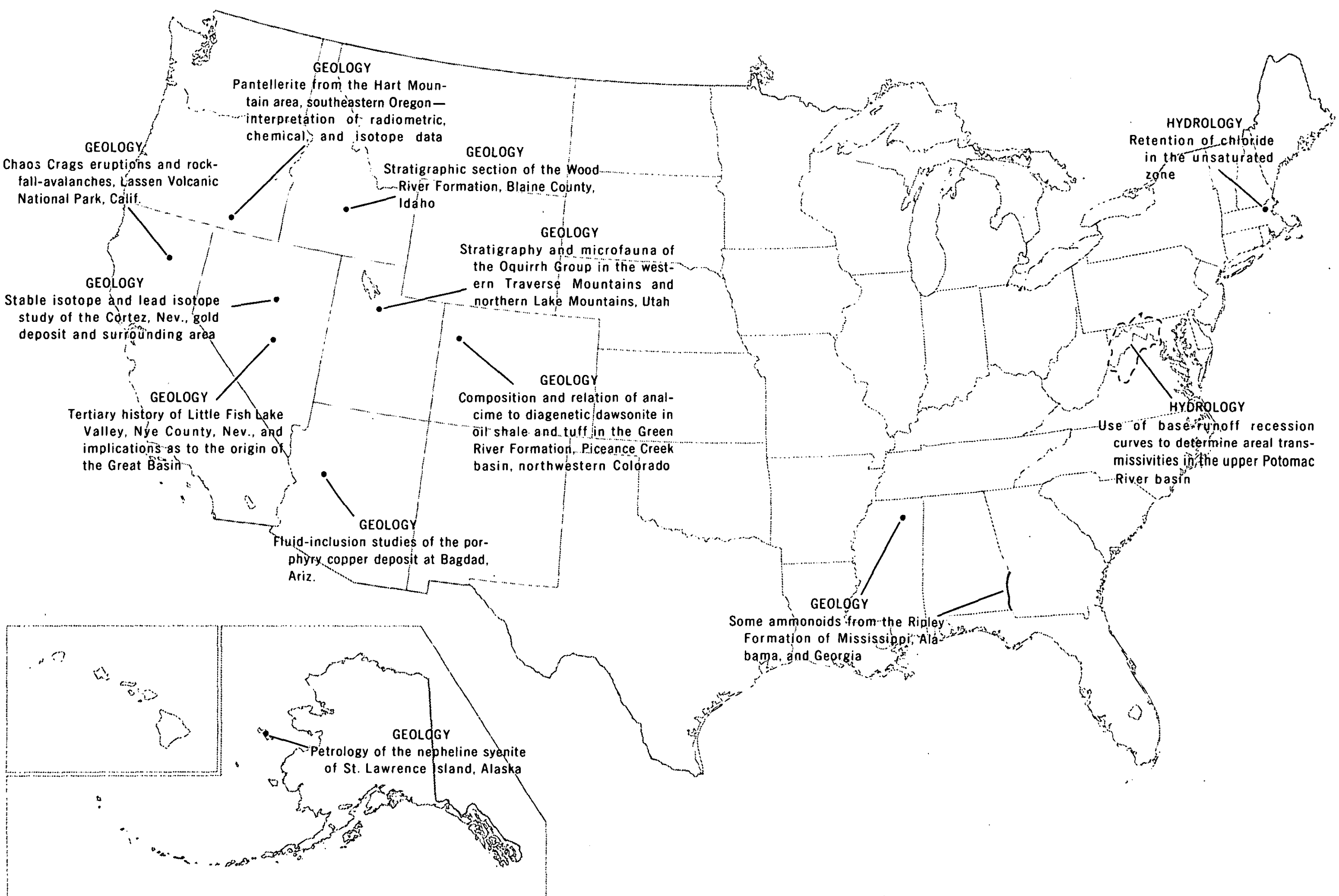

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