

Chapter 20

MODERN AND ANCIENT VOLCANOES

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In: Classic Cordilleran Concepts:
a view from California

ADA:



HOWEL WILLIAMS

Howel Williams introduced a truly modern geologic approach to problems of volcanism in California and the Cordilleran region. Williams, born and reared in Liverpool, came to geology through earlier interests in geography and archaeology. Work in the Ordovician strata of Wales had brought him into contact with the abundant volcanic rocks there and had led him to visit classic volcanic areas in Germany and France. That experience, in turn, set his lifelong interest in problems of volcanism and brought him to California, eager to work on younger volcanic fields. In 1926 Williams arrived in Berkeley to study under A. C. Lawson at the University of California and immediately began his first investigation of California's volcanic geology at the Sutter (Marysville) Buttes in the Sacramento Valley.

The summer of 1927 found Williams' attention drawn to the area of the 1914–1917 eruptions of Lassen Peak, and he became deeply interested in geologic problems of the surrounding young volcanic field. Over the next several years he produced several important papers on that region, including a monograph on the geology of Lassen Volcanic National Park.

It was difficult to select just one of these papers for the purpose of this volume, but it is possible to reproduce here a single complete paper that represents fully the characteristically insightful, beautifully illustrated, and broadly applicable aspects of his work. Thus, we have chosen to reproduce his 1929 paper on the

volcanic domes of the Lassen Peak area, in which he demonstrated the existence and origins of a large cluster of dacitic domes on the northern flank of an eroded older andesitic stratovolcano.

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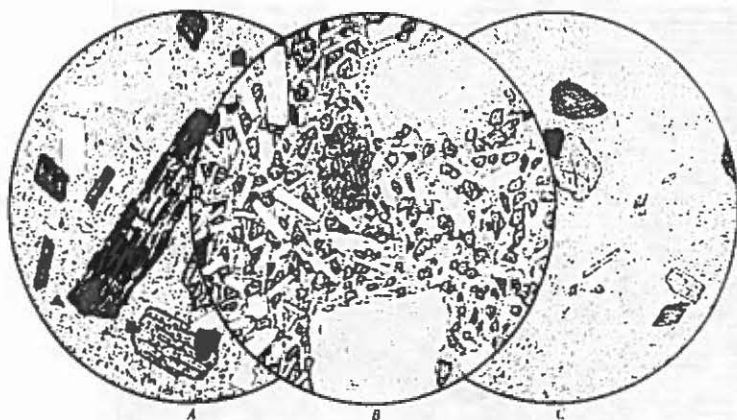


Fig. 17. Andesites of the Brokeoff cone. A. South slope of cone, on fire trail at 8050 feet (298). Phenocrysts of medium andesine, basaltic hornblende and augite, in a base composed of glass and feldspathic residuum. B. Typical augite andesite of the Huckleberry series, near Huckleberry Lake (304). Phenocrysts and microliths of acid labradorite with intersertal granules of augite and magnetite in a feldspathic matrix. C. Glassy andesite at base of Brokeoff cliff, elevation 8500 feet (310). Phenocrysts of andesine, brownish green hornblende, augite and hypersthene in a pale yellowish brown glass crowded with belonites, chiefly of plagioclase.

Example of Howel Williams' thin section sketches. (From Williams, H., 1932b)

THE VOLCANIC DOMES OF LASSEN PEAK AND VICINITY, CALIFORNIA.

HOWEL WILLIAMS.

INTRODUCTION

Since the spectacular rise of the spine of Mont Pelée in 1902, the attention of geologists has been drawn repeatedly to the fact that volcanoes are able to force more or less solid lava upwards within their conduits. In 1904, Russell¹ discussed the diagnostic characters of such "massive-solid eruptions"; in 1907, under the caption 'Staukuppen' (plug-domes), Bergeat² also described protrusions of Peléan type; and in 1916, Powers³ briefly reviewed the literature relating to Pacific domes. More recently, the rise of the dacite plug in the crater of Lassen Peak has been ably considered by Day and Allen;⁴ the phenomenal growth of the Santa Maria dome in Guatemala during 1922-25 has been recorded by Sapper⁵ and the upheaval of the Fouqué Kaméni dome at Santorini in 1925 has been dealt with by Washington⁶ and others.

The purpose of this paper is to attract notice to the remarkable development of similar domes in the Lassen Volcanic National Park, California. Here, within the space of 50 square miles, there are no less than 13 domes, chiefly of glassy dacite. Most of them are clustered on the flanks of the old Brokeoff volcano; the largest is Lassen Peak itself and the most recent is only 200 years old. For the present purpose, it will be best to describe the recent domes first.

THE DOMES OF THE CHAOS CRAGS.

The northern slope of Lassen Peak sweeps down 2,500 feet to a confused cluster of rocky peaks, expressively termed the Chaos Crag. These peaks attain an elevation of 8,545 feet

¹ Russell, I. C., Criteria relating to massive-solid volcanic eruptions, this Journal, 17, 253-268, 1904.

² Bergeat, A., Staukuppen, Neues Jahrb., Festband, 310-329, 1907.

³ Powers, S., Volcanic Domes in the Pacific, this Journal, 42, 261-274, 1916.

⁴ Day, A. L., and Allen, E. T., The Volcanic Activity and Hot Springs of Lassen Peak, Carnegie Instit., Washington No. 360, 1925.

⁵ Sapper, K., Der vulkanische Tätigkeit in Mittelamerika im 20. Jahrhundert, Zeitschr. für Vulkanologie, Band IX, Heft 4, 158-200, 1926.

⁶ Washington, H. S., Santorini Eruption of 1925, Bull. Geol. Soc. America, 37, 349-384, 1926.

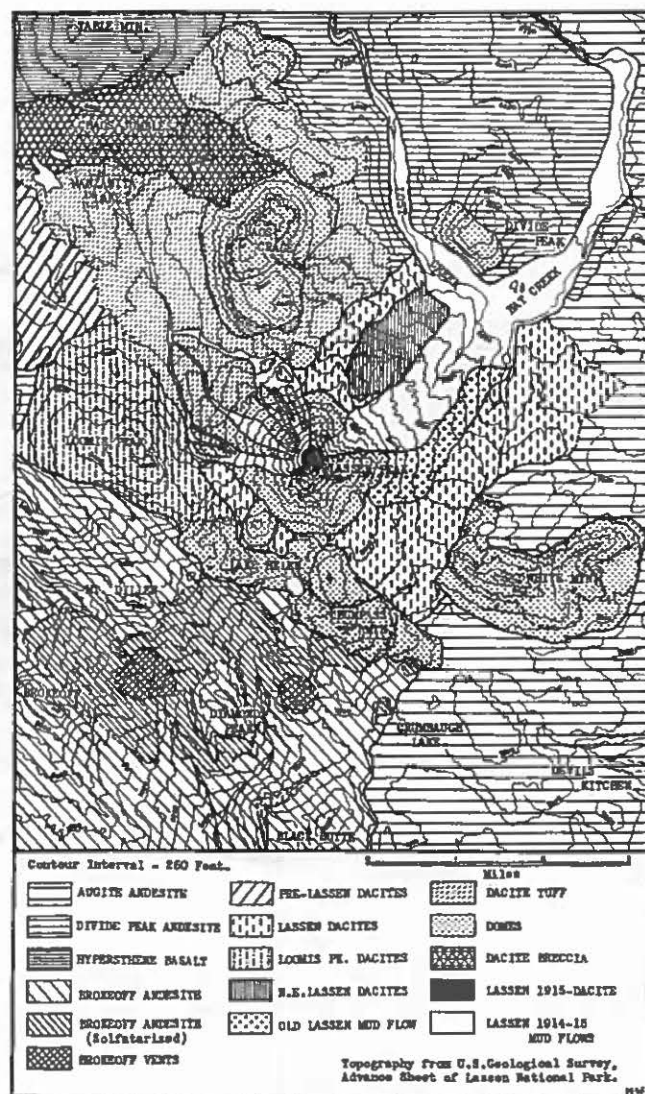


Fig. 1. Geologic sketch-map of Lassen Peak and vicinity.

and stretch northwards for a mile and a half. In an east-west direction, they extend for about a mile (Fig. 1). Their upper surface is hardly more than a wilderness of dacite blocks, and their sides are almost wholly encompassed by great aprons of talus.

It has long been known that these crags represent one of the latest volcanic eruptions of the Lassen area. Brewer and King,⁷ who visited them in 1863, cite the testimony of several persons, that, from 1854 to 1857, these crags "were constantly emitting large quantities of steam and gases." Diller⁸ mentions "Chaos" as having been formed about two centuries ago, and the writer⁹ has given independent evidence to the same effect. From the northern base of these crags, a gentle slope descends toward Manzanita Lake and Lake Reflection. Upon this slope rests a hummocky pile of angular dacite boulders, about two and half square miles in extent. The surface of this deposit, like that of the Chaos Crags, is almost entirely devoid of vegetation, and resembles the bare moraine of an Alpine glacier. This remarkable accumulation of rocks is known locally as the Chaos Jumbles. It was formed, as we shall see, by the partial collapse of the Chaos Crags.

It is not only the recency and hence the almost perfect preservation of the original features of these domes that invites attention; the structures here displayed by the dacites are much more apparent than elsewhere and permit us to draw conclusions regarding the mode of upheaval. Only by analogy with the Chaos Crags is it possible to understand many of the obscure features of Lassen Peak and adjacent domes. The history of events at Chaos is as follows:

(a) *Pyroclastic eruptions:* It has often been remarked that the upheaval of volcanic domes and spines is initiated and may be followed by explosive eruptions. Ash-explosions had occurred at Lassen Peak for a period of one year before the lava-plug rose to the surface of the crater in May, 1915. Similarly, pumice eruptions preceded the rise of the obsidian spines in the Mono Craters, California; the formation of the domes of Novarupta (Alaska), of Santa Maria (Guatemala), and of Tarumai (Japan), were also heralded by pyroclastic

⁷ In Whitney, J. D., Geological Survey of California, 1, 315, 1865.

⁸ Diller, J. S., Lassen Peak—our most active volcano, Bull. Seismol. Soc. America, 6, 2, 1916.

⁹ Williams, H., A Recent Volcanic Eruption near Lassen Peak, Univ. Calif. Publ. Bull. Dept. Geol. Sci., 17, 262, 1928.

eruptions. The protrusion of the dacite domes of the Chaos Craggs likewise succeeded a series of tuff-explosions. The

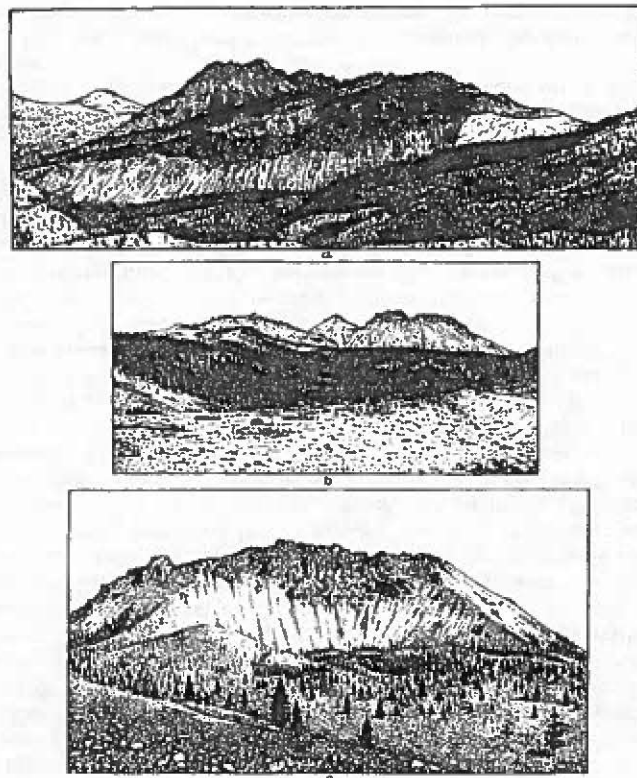


Fig. 2. The Chaos Craggs. *a*: looking east. Shows ruined lapilli-cone and tuff-mantled hills in the foreground; also, the two dacite domes, the earlier well-banded and the later structureless. *b*: looking west. Shows the moat between the domes and the long talus banks. In the foreground is part of the 1915 mud-flow from Lassen Peak. *c*: looking south. Shows the craters at the northern base of the later dome and part of the avalanche-deposit, the Chaos Jumbles.

products of these explosions are widespread (Fig. 1). From a study of the distribution of lapilli and bread-crust bombs in the dacite-tuff, it is manifest that a more or less north-south

line of vents formerly existed on the present site of the Chaos Craggs. At the southern end of the crags, a well-preserved remnant of one of these lapilli-cones may still be seen (Fig. 2a). The freshness of the biotite in the bread-crust bombs suggests that the temperature of the eruptions was comparatively low.¹⁰

At the close of this initial explosive phase, there must have been a vast, hilly field of lapilli passing outward into a wide plain of sand-like tuff. Over much of this area the vegetation was destroyed, so that the barren, white tuff-sheet must have resembled the desolate Pumice-Flats about Mono Lake.

(*b*) *Dacite protrusions*: Two dacite domes, each of them originally a square mile in extent, were then protruded through the tuff- and lapilli-cones, and one of them was elevated at least 1,800 feet. The earlier, southern mass has an approximately arcuate form and partly encloses the later dome, from which it is separated by a conspicuous, moat-like depression (Figs. 2a and 2b). It is possible that the earlier dome was once circular in plan and that its crescentic form results from explosions that destroyed its northern side, just as they are known to have destroyed the northern face of the later dome. A somewhat similar sequence of events occurred during the rise of McCulloch and Metcalf domes in the Bogoslof Islands, Alaska.¹¹

Except along the periphery, the banding of the dacite in the earlier protrusion is invariably steep and is usually vertical. Marginally, the banding has a low inward dip, as if the lava had just begun to spread laterally before it was chilled. Analogous structures were observed in the dome of Novarupta, Alaska,¹² and may be studied in the Panum spine near Mono Lake. That the Chaos dacite was largely solid when it reached its present position is apparent not only from the attitude of the banding, but from the fact that the surface of the dome is chiefly made up of a tumultuous pile of loose, angular blocks. These rock piles may result from the fracture of a solid crust owing to differential upward movement in the

¹⁰ Cf. Day, A. L., and Allen, E. T., op. cit. 49, 1925.

¹¹ Jaggar, T. A., The Evolution of Bogoslof Volcano, Bull. Amer. Geog. Soc., 40, 385-400, 1908.

¹² Sapper, K., Vulkankunde, Stuttgart, 1927, footnote 199-200. "Die Neubildung eines Doms am Novarupta-Vulkan (nahe Katmai) 1912 zeigte vermöge der Bandstruktur des Gesteins deutlich, dass die Bänderung den Dom umgibt, nahe der Basis flach einwärts fällt, nahe dem Gipfel aber steil, fast senkrecht ist." Dr. C. N. Fenner has kindly sent me photograph illustrating this phenomenon.

still viscous lava beneath, and in part also may be due to quick changes of temperature, especially sudden chilling, and to steam explosions. The dacite is abnormally rich in glass, which must have been subject to much strain both during and after consolidation.

The superficial rock piles are not devoid of regular arrangement; on the contrary, they are disposed in great, arcuate ridges concentric with the outer margin of the dome, as if they express some internal structure. Viewed from the west (Fig. 2a), they appear as a series of terraces, inclined northwards at a low angle. If the dome were originally circular and the ridges were continuous, they must then have resembled the rims of a group of hollow cylinders one within another, the highest at the center. If such were the case, it is reasonable to suppose that the outermost cylinder solidified first and that the others rose successively, the innermost last, as a narrow pencil of lava. Fouqué¹³ noticed circular cracks on the surface of the Georgios dome, Santorini, in 1866, and attributed them to violent explosions. Washington¹⁴ saw similar fissures among the rock piles at the base of the Fouqué Kaméni dome, Santorini, in 1925, his explanation being that they were "caused by a differential sinking of the dome itself relatively to the lava plateau on which it stands." Such a sinking might be facilitated by the outpouring of lava from below and by the loose, blocky character and weight of the dome itself. It is worthy of note that the loose blocks comprising much of the surface of the domes at the Chaos Crags are rarely small. Gravel-like accumulations are exceptional. Over large areas, the blocks average a yard in length; elsewhere it is uncommon to find blocks less than 10 feet in dimensions. Many blocks measure as much as 20 feet long and a few reach a length of 30 feet. They are generally smooth-faced and angular, and frequently their sides are slightly concave, suggesting conchoidal fracture on a large scale.

The high talus banks that partly surround the domes are, in large measure, an original character. To some extent the domes rose, as it were, through their own talus. In this respect, as in many others, they resemble the twin domes of Santa Maria, Guatemala, so beautifully illustrated in Sapper's work.

¹³ Fouqué, F., *Santorin et ses Éruptions*, 49, and 75, Paris, 1879.

¹⁴ Washington, H. S., *op. cit.*, 370, 1926.

The later, northern protrusion at the Chaos Crags, like the earlier, consists of a glassy hornblende-mica dacite but the lava here is almost wholly free from banding and is more abundantly charged with purplish, basic, hornblendic secretions. Rarely can any structure be detected within the mass, and it is then restricted to a faint, vertical banding near the core and to a low, inward-dipping banding at the edges. This marginal arrangement of the flow-planes is thus similar to that observable in the earlier dome; it is due in part to the weight of superincumbent lava and suggests an abortive attempt at lateral flow. There appears to be no regular distribution of the basic secretions nor do they exhibit any common direction of elongation. Here, as in the earlier dome, the surface is largely made up of loose blocks in irregular heaps. Most of the blocks have suffered superficial oxidation by steam, for the hornblende and mica on their outer faces are of a deep red color, their normal color being green.

(c) *Explosive eruptions.* The later dome had perhaps attained its present elevation when the northern face of the mass collapsed, producing a gigantic avalanche or rock stream, the Chaos Jumbles. The immediate cause of the collapse is uncertain, but two possibilities suggest themselves: either the dome had become so high and unstable that its collapse was inevitable, or its breakdown was precipitated by the blasting of craters at or near its base. At the northern base of the dome there are two deep, crateriform depressions (Fig. 2c), around which there are signs of solfataric activity. These depressions must have been partly formed after the collapse of the dome, for they have been blasted through the loose debris. It is possible, however, that they originated immediately before the collapse, and that their formation hastened that inevitable event. About 150 million cubic yards of dacite blocks were thus hurled onto the tuff-sheet that had been formed by the initial pyroclastic eruptions. The avalanche rushed northward and rose 400 feet up the opposite slopes of Table Mountain, almost two miles distant from the craters. Elsewhere, the writer¹⁵ has offered evidence to show that the old tuff-sheet over which the avalanche passed had been largely converted into mud by rains that attended the steam explosions. The mobility of the avalanche must have been increased considerably by this muddy surface. The size and character of these explosions are almost precisely similar to

¹⁵ Williams, H., *op. cit.*, 257-258, 1928.

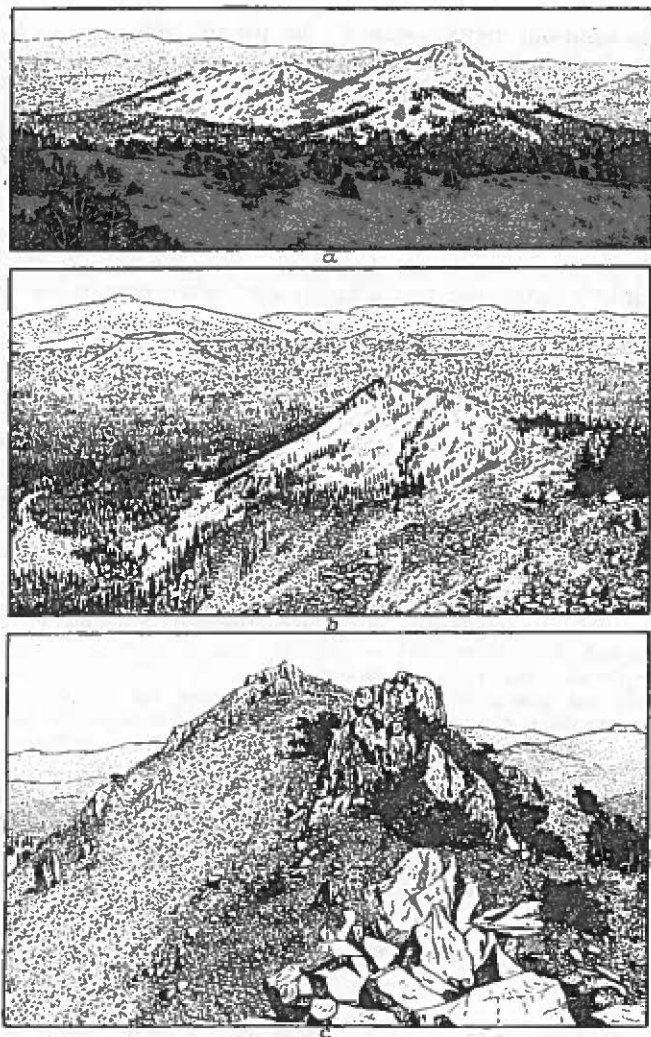


Fig. 3. The White Mountain Dome. *a*: looking east from the slopes of Lassen Peak, showing the great talus banks. *b*: east end of the ridge. The Central Plateau of augite andesite and Hat Mountain cone in the middle distance. In the background, from left to right, the dome and cone of Prospect Peak, the quartz basalt Cinder Cone and Fairfield Cone. *c*: part of the summit ridge, showing vertically jointed rock pinnacles protruding through coarse, angular talus blocks.

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those of the eruption that occurred at Bandai-san, Japan, in 1888.¹⁶ In the case of the Chaos dome, we may suppose that a major cause of its upheaval was the vapor tension in a subjacent crystallizing magma, and we may postulate, as Day and Allen have done in the case of the plug that rose in the crater of Lassen Peak in 1915, that the lava continued to rise until the propelling force was violently released by the blasting of vents at or near its base.

WHITE MOUNTAIN DOME.

We are now in a position to discuss the older domes of the Lassen region. Of particular interest is the dome of White Mountain, situated about two miles southeast of Lassen Peak (map, Fig. 1). At first sight, the mountain appears to be little else than an enormous pile of blocks. In a few places, crags and pinnacles of 'solid' rock do project through the talus banks, but they are of insignificant proportions by comparison with the volume of superficial debris (Fig. 3c). It is this extraordinary development of talus that first impresses the onlooker. It is not a simple product of weathering, and by analogy with the talus banks of the Chaos Crags, it seems to be due to the fracturing of the lava during its actual emplacement. In a word, it appears to be an original feature of the dome. Probably the loose jumble of blocks passes downward into brecciated andesite, in which the fragments are only semi-detached, and this in turn grades into massive, unbroken lava.

Griggs,¹⁷ writing of the dome of Novarupta, states that in cooling, the upper portion became "a confusion of broken blocks, heaped topsy turvy over the surface, concealing for the most part the bedrock and giving the lava plug the appearance of a huge stone pile." Washington¹⁸ vividly describes the rapid changes in the form of the Santorini dome of 1925. He notes:

These changes were obviously caused by the continuous redistribution of the constituent loose blocks by the violent eruptions. . . . The dome was not covered by a more or less continuous "carapace," but . . . was (and probably now is) simply a mass of

¹⁶ Bonney, T. G., *Volcanoes*, 35-36. London, 1912.

¹⁷ Griggs, R. F., *The Valley of Ten Thousand Smokes*, Nat. Geog. Mag., 240, 1922.

¹⁸ Washington, H. S., *op. cit.*, 361-365, 1926.

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loose blocks. The dome showed no definite crater. . . . The great vulcanian explosions took place from different places on the upper part of the dome. . . . Occasionally the dome, so to speak "blew its whole head off."

Fouqué¹⁹ refers to the rise of the Georgios dome in 1866 thus:

L'accroissement de l'îlot se faisait sans secousse, sans projection, silencieusement, mais avec une telle rapidité, que M. de Cigalla le compare au développement d'une bulle de savon. Il s'opérait du dedans au dehors, comme par un mouvement d'expansion, les blocs semblaient partir du centre de la surface et progresser de là vers la périphérie; on avait peine à suivre du regard la marche de tous ces blocs pierreux et leurs déplacements incessants. . . . Tout autour de nous, nous entendons un craquement incessant dû à la rupture des blocs pendant la contraction causée par leur refroidissement; ce bruit est accompagné d'un cliquetis semblable à celui que donne le choc de débris de porcelaine; il est produit par la chute des fragments détachés des cassures récentes.

Again, Jaggard²⁰ describes McCulloch Peak in the Bogoslof Islands in these words:

(It was) of rounded cone shape . . . and appeared at first sight like a steaming heap of boulders. The top in profile was flattish, but lumpy, made of hard rock, and without any crater. There were rocky crags at the core and summit of the mass, with slide-rock about its foot-slopes fed by the tumble from the rising cliffs above. Not that the tumbling or rising could be seen—it was too slow for that. All was deathly quiet—but dangerous looking.

It is needless to cite other instances of similar growth among volcanic domes; the fracturing of their crusts and the contemporaneous development of talus banks appear to be almost diagnostic features of massive protrusions.

At White Mountain, one is also impressed by the scarcity of any regular structures within the 'solid' portions. In this respect, it resembles the northern dome at the Chaos Crags, and, as we shall see, the dome of Lassen Peak. Only at the western end of White Mountain do the andesites exhibit flow-banding. Here, close to the margin of the dome, the lava assumes a slabby or even platy structure and the banding lies flat or has a low inward dip. Further within the mass the

¹⁹ Fouqué, F., *op. cit.*, 42 and 54, 1879.

²⁰ Jaggard, T. A., *op. cit.*, 392, 1908.

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flow-planes become increasingly steep and at 400 yards from the margin they are generally vertical. It would seem, therefore, that here, as at the Chaos Crags, Novarupta and other domes, the flattening of the flow-planes toward the base and periphery suggests an abortive attempt at lateral spread. Throughout most of White Mountain, however, banding is entirely wanting.

Along the northern edge of the dome there are curved 'lager' joints, convex outwards. Elsewhere, the joints are usually vertical (Fig. 3c), but the joint-planes are oriented without apparent regularity. Over large areas, particularly near the western end of the dome, the andesite blocks are deeply oxidized and have been converted locally into a mixture of opal and kaolin by solfataric action. Hereabouts, the joint faces are commonly covered with brilliant white, yellow and red incrustations of opal, sulphur and iron oxide.

Petrographically, the lava is a pyroxene andesite, poor in glass, rarely vesicular and carries abundant hornblende secretions. Save for this last character and for the scarcity of flow-banding, the lava does not differ materially from the pale andesites that form the whole region about the head of the Warner Valley to the east. The dips of these andesite flows point to a vent on or near the site of White Mountain. It is therefore suggested that the White Mountain dome rose in the old crater after the cessation of the quiet, liquid effusions.

THE DOME OF LASSEN PEAK.

The edifice of Lassen Peak rises conspicuously above the surrounding country. Like White Mountain, its sides are almost entirely covered with banks of talus, some of which have a vertical sweep of over 3,000 feet. The exact limits of the peak are poorly defined, but its volume cannot be less than three-fifths of a cubic mile and it must have been elevated about 2,500 feet above the old Lassen crater. Except for the cliffs illustrated in Fig. 4, 'solid' exposures are few and small, and are characterized by an almost complete lack of any regular structure. To many, this must seem the most remarkable feature which the mountain presents, though heretofore no particular record seems to have been made concerning the fact. Excluding the products of the 1914-15 eruptions, the peak is composed of a grey or pink, glassy hornblende-mica dacite carrying an abnormal abundance of dark,

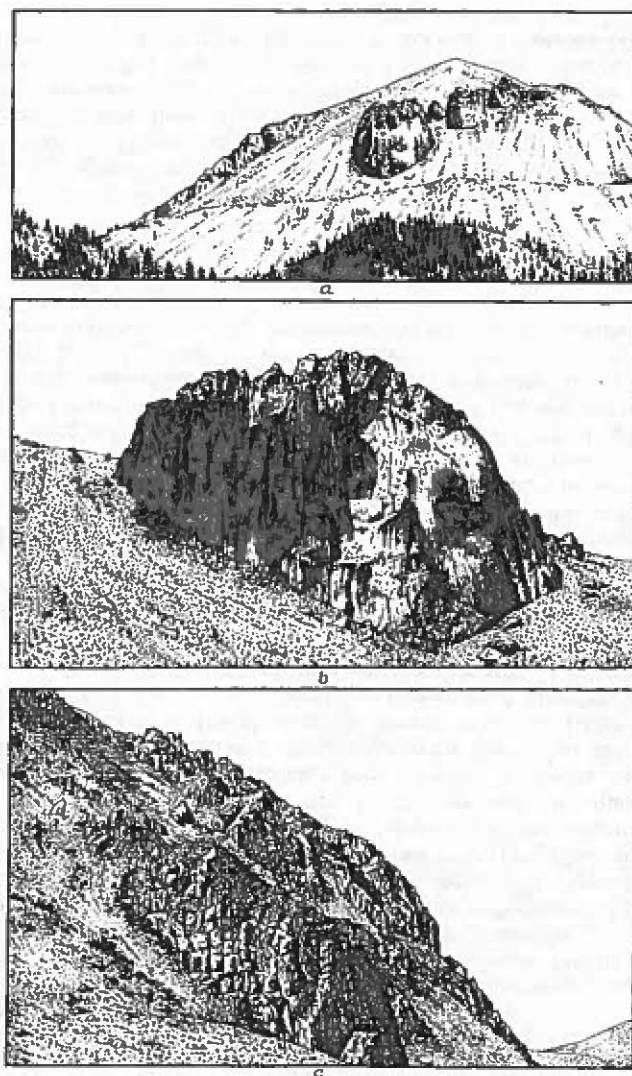


Fig. 4. *The Dome of Lassen Peak.* *a:* south slope from above Lake Helen, showing smooth sides of the plug-dome and concentric banks of talus. *b:* nearer view of the smooth face of the dome, showing the rounded form and fine vertical striation; height of cliff, about 500 feet. *c:* crags near the summit, southeast side, showing vertical joints and long talus slides.

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hornblendic secretions. Viewed from a few yards' distance, the rocks might well be mistaken for unbedded volcanic breccias. A crude banding may be seen among the crags on the southeast side of the peak; it rolls irregularly at low angles with a general pitch toward the interior of the dome.

If the flow-structures be considered vague, the joint-system is no less obscure. Vertical joints predominate far over all others (Fig. 4c), but the orientation of the planes is so haphazard as to defy any attempt at mapping. On the south side of the peak, the joint-planes may be curved. The high and beautifully smooth cliff overlooking Lake Helen affords an excellent instance of this (Fig. 4b). The smoothness of this cliff-face is not due to glacial polishing. Proof is impossible, but the impression is strong that this is part of the original face of the dacite dome, and that its broad vertical fluting and narrow striae and polishing are due to friction of the solid or almost solid crust of the mass as it rose to the surface through a circular orifice. The curved joints that lie parallel to the face are thus attributed to contraction on cooling. Such a polishing of the sides of massive protrusions has been described elsewhere; for example, one face of the Pelée spine was smooth, and Jaggar²¹ says of the Metcalf dome at Bogoslof that its

"resemblance to a beak was increased by regular markings on the rounded surface as though the horn had been shoved up at intervals. Apparently, it had been squeezed out, like paste from a tube, in a semi-plastic condition, and had gradually shaped a roundish cavity for itself in the lava about it."

Possibly much of the outer face of the Lassen dome now concealed by talus may be smooth like the cliff above Lake Helen, and it is likely that if the talus were stripped away the solid core of the Lassen protrusion, like those of the Chaos Crags, would be found to be more or less cylindrical.

Reference to the map (Fig. 1) shows that Lassen Peak is partly surrounded by flows of dacite. Most of these dacites are black, glassy lavas, mineralogically similar to that of Lassen itself, and likewise rich in hornblendic secretions. One of the flows, that of Loomis Peak, consists of a lava that can only be distinguished from the dacite of Lassen Peak by the prominence of its banding. The attitude of the flows indi-

²¹ Jaggar, T. A., op. cit., 394, 1908.

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cates that they issued from a crater on or near the site of Lassen. It seems reasonable to infer, therefore, that the almost structureless mass of Lassen Peak represents the upheaved plug of this crater.

Plug-domes of similar type are far from uncommon: Santa Maria (Guatemala), Galunggung (Java), Ko-usu, O-usu and Tarumai (Japan) may be mentioned as examples. In a measure, Lassen Peak may have risen as an endogenous dome, as did the trachyte *puys* of the Auvergne and Ascension Island, but chiefly, it seems, the mass was propelled from below as a homogeneous body or 'stopper' by the continued accession of fresh magma and by the pressure of aqueous vapor. Its rise appears to have been attended by steam explosions and by mud flows comparable with those that accompanied the rise of the plug in the summit crater of Lassen in 1915. The signs of some of these earlier mud flows may be seen along the eastern margin of the recently "Devastated Area" and along Lost Creek. Indeed, the upheaval of the 1915 lava into the summit crater of Lassen was a miniature copy of the rise of Lassen itself through the pre-Lassen crater.

The inner structure of Lassen Peak is, of course, unknown. It is probable, however, that an ill-defined central conduit exists and that the lava becomes increasingly vesicular toward it. Should fresh magma rise beneath the dome, this central portion would suffer fusion first and tend to be uplifted. This is what may have happened during 1914-15. Central spines rose from the summits of the Santa Maria, Pelée and Metcalf domes, and probably the mechanism of emplacement of the 1915 lava of Lassen Peak was the same. There, however, the dacite did not have the properties requisite to the formation of a narrow spine.

DOMES SOUTH OF LASSEN PEAK.

A cluster of small domes lies at the southern base of Lassen Peak, separating it from the exposed parts of the Brokeoff volcano. These domes were protruded through the black, glassy dacite flows that issued from the old Lassen crater. For instance, Eagle Peak is made up of a pink, massive and poorly banded dacite like that of Lassen Peak, whereas its base is almost encircled by a nearly horizontal flow of black, columnar dacite. Five hundred yards north of Lake Helen, the long talus slope of Lassen abuts on a small dacite pro-

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trusion, almost circular in plan, which shows a marginal, concentric banding that stands vertically or dips inwards at steep angles and encloses an unbanded core. Bumpass Mountain, again, is for the major part a structureless mass of gray dacite the surface of which is littered with great piles of angular blocks. Closely-set, steep or vertical joints and low, inward-dipping flow-planes may be distinguished at the margins of the dome. Along its south side, adjacent to the hot springs of Bumpass Hell, the dacite has suffered hydrothermal alteration. This protrusion and that lying immediately to the north closely resemble the talus-mantled dome of White Mountain. The fantastic crags of Vulcan's Castle, one mile northwest of Lake Helen, appear to represent part of another dacite dome, but there is reason to suppose that hereabouts the domal eruptions were accompanied by short, thick flows. It must also be stated that the forms of these domes have been seriously modified by glaciation.

Finally, about 8 miles south of Lassen Peak, close to the Park Highway, there are two other domes, composed of acid andesite rich in hornblendic secretions, namely Morgan Mountain and the hill west of the 'Boy Scout Camp.' Each measures approximately two miles long and a mile wide. They exhibit marginal banding and massive cores like the domes already mentioned and are associated with thick, stumpy flows. They lie near the southern base of the old Brokeoff volcano.

DOMES NORTH OF THE CHAOS CRAGS.

The irregular hills that lie between the Chaos Crags and Table Mountain are largely covered by glacial drift, but their forms suggest them to be steep lava-domes. Here, as on other domes, the surfaces are chiefly made up of angular dacite blocks lying about in great disorder. The dacite is not of the usual hornblende-mica variety, but is a pyroxene-bearing type, rich in hypersthene phenocrysts set in a glassy base, and is almost devoid of hornblendic secretions. Banding is seldom developed and seems to be oriented haphazard.

SUMMARY CONCERNING THE LASSEN DOMES.

The domes referred to in the preceding pages consist chiefly of glassy, acid andesites and dacites, rich in hornblendic secre-

tions. Most of them are singularly devoid of well-defined structures, except marginally where they reveal a low, inward-dipping banding. In the cores of the domes banding is either absent or is vertical; the dominant joint-planes are also vertical but of irregular orientation. All the domes are characterized by loose, blocky surfaces, due to the break-up of their solid crusts during protrusion. Two domes—those of the Chaos Crags—were protruded through a line of tuff-cones; two others—Lassen Peak and White Mountain—rose through old craters that had previously erupted fluid dacite and andesite, respectively. These four domes may thus be termed plug-domes (*Staukuppen*) and appear to represent the upheaved infillings of volcanic pipes.

It is worthy of note that although so many of these domes are clustered on the flanks of the old, hypersthene andesite, Brokeoff volcano, no domes rose into the Brokeoff caldera itself. It must be remembered, however, that the Brokeoff caldera is now the center of an extensive area of fumaroles and hot springs, and it is possible that this solfatarism is the surficial expression of a concealed intrusion, perhaps of dacitic character. That the Brokeoff caldera was faulted and collapsed after the emission of some of the glassy dacites from the Lassen crater is clear from the fact that a flow of Lassen dacite occurs on the opposite side of the Brokeoff caldera, on Black Butte (map, Fig. 1). Perhaps the suggestion may be allowed that the collapse of the Brokeoff caldera was occasioned by the protrusion of the adjacent domes of dacite. Such a wholesale migration of magma as that involved during the dacite protrusions may well have withdrawn the support from beneath the Brokeoff cone.

By analogy with the observed rate of protrusion of such domes as those of Santa Maria, Tarumai and Santorini, it can hardly be doubted that the rise of the Lassen domes was a rapid process. Two years after its first appearance, the Santa Maria dome was 500 meters high and 1,200 meters wide at the base. Considered solely on this basis, it seems that Lassen Peak may have reached its present elevation during a period of about five years, and that some of the smaller domes may have grown in a year or so.

Excepting the domes of the Chaos Crags, which are about 200 years old, all the Lassen protrusions are preglacial. It should be borne in mind, however, that glaciation persisted among these mountains until a very late date.

THE DIVIDE PEAK DOME.

The form of the augite andesite cone of Divide Peak is surprisingly little modified by glaciation. The same is true of other large cones in the Lassen National Park, especially of Red Mountain, Prospect Peak and Mount Harkness. On the summit of Divide Peak, there still remains a well-preserved cinder cone. On the southwest side of Divide Peak, the andesite is intruded by a large body of dacite, finely revealed in the long line of cliffs overlooking the head of Lost Creek (Figs. 1 and 5). Toward the base, the dacite has a strongly developed columnar structure, the columns standing vertically. Flow-banding is conspicuous throughout, especially at higher levels; throughout most of the dome it lies flat, but near the top it is vertical or dips to the east and southeast at angles of from 40° to 70°. The dacite is a glassy, hornblende-mica variety, not unlike that of the Chaos Crags and Lassen Peak, and is charged with abundant hornblende secretions, particularly toward the base.

Although the actual contacts between the dacite and andesite cannot be observed, there is reason to suppose that the margin of the dacite has a steep outward dip and may be vertical in places. Thus, toward the southern end of the protrusion the horizontal banding of the dacite bends over to the vertical, and at several localities the dips of the andesites are seen to have been reversed and tilted away from the dacite at high angles.

Since the form of the Divide Peak cone has been so little affected by glaciation, it is probable that the present form of the dacite dome is also not very different from its original shape. If such be the case, then the dacite cannot have risen far above the surface of the andesite cone. The area of reversed dips among the andesites near the margin of the dome is not extensive; again, there cannot have been more than a thin cover of andesite over the dacite, and it is more likely that no such cover ever existed; and, further, there is no marginal assimilation of andesite. It follows that the dacite did not displace much andesite and is probably of no great thickness. Perhaps it is of mushroom form and has an internal structure such as that depicted in Fig. 5. A viscous lava rising through a narrow orifice and spreading

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in this manner would develop a more or less concentric structure (Zwiebelstruktur), as Reyer²² has shown experimentally.

The dome of Divide Peak thus presents a close similarity to many of the trachyte domes described by Daly²³ from Ascension Island; that is, it is a true endogenous dome that grew

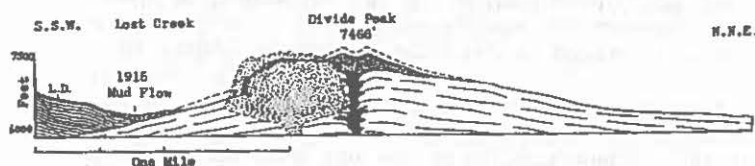


Fig. 5. Section through Divide Peak andesite cone and dacite dome. The summit of the former consists chiefly of bedded pyroclastic rocks. Flows of glassy dacite from the crater on the N. E. flank of Lassen Peak (L. D.) overlies the andesites on the south.

by expansion from within. It was not upheaved as a virtually solid plug, as were most of the other Lassen domes. Its location on the slope of the Divide Peak cone is comparable, however, with that of the other domes on the flanks of the older Brokeoff volcano.

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²² Reyer, E., in Sapper, K., *Vulkankunde*, 199, 1927.

²³ Daly, R. A., *The Geology of Ascension Island*, *Proc. Amer. Acad. Arts and Sci.*, 60, 23-38, 1925.

Volcanism in California

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INTRODUCTION

A rich literature exists on volcanism and volcanic geology in California, although only a single eruptive episode—that of Lassen Peak in the second decade of the twentieth century—has been witnessed closely during the period of written history. Without doubt the most influential early investigator to bring a modern geologic approach to bear on problems of California and west coast volcanism was Howel Williams, and among his earliest studies was his work in the Lassen region. This paper briefly reviews some of Williams' relevant work and its influences, then summarizes later studies of volcanism in California.

In 1926 Williams came to study under A. C. Lawson at the University of California, and the rest of his career remained centered at Berkeley. Following studies at the University of Liverpool and Imperial College on Ordovician strata in Wales, with their abundant volcanic rocks, and visits to classic volcanic areas of Germany and France (McBirney, 1985), he arrived in California eager to work on volcanic problems and soon began a study at the Sutter (Marysville) Buttes in the Sacramento Valley (Williams, 1929a).

Interest in the 1914–1917 eruptions of Lassen Peak, then still in recent memory, attracted Williams there in the summer of 1927, where he found his attention drawn to a number of interesting issues. In particular, he recognized the Chaos Crags, aptly named piles of broken lava blocks that rise as much as 430 m above the north base of Lassen Peak, to be a cluster of volcanic domes—protrusions of viscous lava that had mounded above their vents with only limited lateral flowage. He also recognized the Chaos Jumbles, a hummocky field of lava blocks spreading northwestward from the Crags, as a catastrophic avalanche deposit rather than morainal debris, as thought by earlier workers. Williams recognized that Lassen Peak itself is a much larger volcanic dome, one of the largest known, and made

detailed petrographic observations of the clustered dacitic domes of the Lassen area and their abundant mafic inclusions. These investigations, together with systematic geologic mapping, constituted one of the first detailed modern studies of a volcanic area in California; they were published in a series of topical papers (Williams, 1928, 1929b, 1931) and were summarized, together with a colored geologic map, in a volume of the important publication series produced over many decades by the Department of Geological Sciences of the University of California (Williams, 1932b).

LASSEN PEAK ERUPTIONS OF 1914–1917

An extended series of eruptions began at Lassen Peak in May 1914, climaxed in May 1915, and waned through June 1917, occasioning great scientific as well as public interest. Although these volcanic events were not scientifically well studied during their activity, they were among the first eruptive episodes to be documented through an extensive photographic record.

The first scientist to visit Lassen in order to observe its activity was J. S. Diller, a pioneering geologist who had mapped much of southern Oregon and northernmost California in geologic reconnaissance for the U.S. Geological Survey during the late nineteenth and early twentieth centuries. Diller, by then no longer an active field geologist, accompanied the local businessman and enthusiastic photographer B. F. Loomis to Lassen Peak and the surrounding area in June 1914. The climactic explosions of May 19–22, 1915, were not witnessed directly by scientists, but following those eruptions Diller visited again in 1915 and 1921. Although he published some significant observations (e.g., Diller, 1914a, 1914b, 1916, 1917), Diller did not carry out a systematic study. During the summer of 1915 and for the next several seasons, A. L. Day and E. T. Allen of the Carnegie Institution of Washington undertook a detailed study of the ongoing volcanic activity, as well as the hot springs of the Lassen Peak area. Their

ensuing paper (Day and Allen, 1925) summarized the 1914–1915 eruptions and offered the first integrated interpretation of the devastation produced on the northeast flank of Lassen Peak in May 1915 and the resulting far-traveled debris flows. B. F. Loomis published his own ideas of the explosive eruptions and their interpretation in a small book featuring some of his photographs (Loomis, 1926). These events and studies formed the background against which Williams set his more comprehensive study of the Lassen region.

“THE VOLCANIC DOMES OF LASSEN PEAK AND VICINITY, CALIFORNIA”

It is somewhat arbitrary to select just one of the several papers Howel Williams produced from his work in the Lassen Peak region for the purpose of this volume. In order to reproduce a single complete paper that represents some of the characteristically insightful and generally applicable aspects of his work, however, we have chosen to highlight his 1929 paper on the volcanic domes of the Lassen area. In that paper Williams demonstrated the existence of at least 13 dacitic domes clustered on the northern flank of an eroded older andesitic stratovolcano, the Brokeoff cone.

His observations of Chaos Crags and Chaos Jumbles had led Williams to new conclusions about their origins and had focused his attention on the origin and emplacement of volcanic domes. The importance of domes had begun to become more widely appreciated through a number of early twentieth-century studies. In particular, the catastrophic 1902 eruption of Mont Pelée on Martinique and subsequent activity there (Lacroix, 1904), and the 1922–1925 growth of the Santiaguito dome at Santa María volcano in Guatemala (Sapper, 1926) had demonstrated important aspects of the growth mechanisms of volcanic domes and their relation to violently explosive eruptions. In the paper reproduced here, Williams (1929b) brought these lessons to the domes of the Lassen region and extended them with his careful descriptions and interpretations of the variously exposed domes and related flows and pyroclastic deposits there.

The Chaos Crags are the youngest domes of the Lassen region. Williams described pyroclastic ejecta that form a partly buried crater at the south end of the Crags and a blanket over much of the surrounding terrain. The chaotically blocky surfaces of the domes were demonstrated to have formed by the fracturing of a brittle crust as the domes grew by swelling during emplacement while their interiors retained structures related to viscous flowage. Interpretation of these features in terms of dome-emplacement mechanisms allowed Williams to extend his interpretations to the emplacement of the older domes, Reading Peak (known at the time as White Mountain), Lassen Peak, and others nearby. The domes, at least initially glassy in texture, are dacites. The initial enveloping of the domes by talus-like breccia was shown to be characteristic, although glacial erosion had removed such a carapace from many of the older bodies. The degrees of preservation of carapace breccia provided estimates of the relative ages of various domes. Spines or other smooth-surfaced protrusions characteristically rise above the brecciated surfaces to

expose the interior lithologies and shear surfaces related to emplacement. Individual domes represent monogenetic episodes of growth over periods of months to a few years. The dome on the west side of Raker Peak (then known as Divide Peak) was interpreted to have forcibly displaced the lavas of the older andesitic cone that it intruded and partly overgrew.

The detailed descriptions and interpretations of these bodies in the Lassen Peak region led logically to a comprehensive review of volcanic domes and their origins (Williams, 1932a). The Lassen work and its outgrowths became highly influential publications, setting a high standard for geologic work in areas of young volcanism, beginning a course of study that carried Williams to several other significant volcanoes in the Cascades, and helping to establish his worldwide reputation in volcanology and volcanic geology.

LATER STUDIES AND THE EXTENDED INFLUENCE OF HOWEL WILLIAMS

Williams followed his Lassen work with important investigations at other Cascades volcanoes. A brief study of Mount Shasta (Williams, 1932c, 1934) led to a reconnaissance of the northernmost California Cascades (Williams, 1949). What undoubtedly became his most influential study, that at Crater Lake, Oregon (Williams, 1942), demonstrated the collapse origin of the Crater Lake caldera and resulted in another highly influential comprehensive review, analyzing calderas at volcanoes around the world (Williams, 1941). Meanwhile, Williams visited and studied volcanoes elsewhere, including Tahiti (Williams, 1933) and the Navajo-Hopi country of Arizona (Williams, 1936). Furthermore, he began to attract other young members of the Berkeley faculty to volcanic studies, notably C. A. Anderson, who made significant contributions to understanding volcanic mudflow deposits (Anderson, 1933b) and carried out geologic studies of youthful volcanism in the Medicine Lake Highland (Anderson, 1933a, 1941) and the Clear Lake volcanic field (Anderson, 1936) in northern California.

Williams also gained a prominent academic reputation. Among those who came under his influence and went on to advance volcanological knowledge were Gordon Macdonald, who later made major contributions to the geology of Hawaii (e.g., Macdonald, 1968) and the Lassen region (e.g., Macdonald, 1963). Williams' student Garniss Curtis, after a study of Tertiary volcanism in the central Sierra Nevada (Curtis, 1954), began an important investigation of the 1912 eruption in the Valley of Ten Thousand Smokes, Alaska (Curtis, 1968), although his efforts were soon diverted from a volcanological emphasis to development and application of the newly emerging technology of K-Ar dating (e.g., Curtis et al., 1958). Curtis did, however, join in revising the earlier results of Williams' first California study, at Sutter Buttes (Williams and Curtis, 1977). Following the 1943–1952 eruptions of Parícutin (Williams, 1950), Williams' major volcanological interests turned to Central America. It was there that he encountered the person who was to become proba-

bly his most notable volcanological student and long-time colleague, A. R. McBirney. Separately, together, and with others, Williams and McBirney produced a series of important studies of Guatemalan, Nicaraguan, and Salvadoran volcanoes (e.g., McBirney and Williams, 1965) as well as the Galápagos Islands (McBirney and Williams, 1969). Williams collaborated with fellow Berkeley professors F. J. Turner and C. M. Gilbert to produce a classic textbook on petrography, illustrated with his thin-section drawings (Williams et al., 1954), and later with McBirney on a volcanology textbook (Williams and McBirney, 1979).

OTHER STUDIES OF CALIFORNIA VOLCANISM

Volcanic rocks in California from Precambrian to Holocene have provided numerous important studies, but a brief review of advances made in the path blazed by Howel Williams and his contemporaries at Berkeley inevitably focuses on Cenozoic volcanism. Figure 1 shows the locations of important localities mentioned in the following discussion.

The Cascades–Modoc Plateau–Warner Mountains region

When Howel Williams undertook studies at Lassen, R. J. Russell (1928) was establishing a Tertiary volcanic stratigraphy in the Warner Mountains, at the edge of the Great Basin. The andesitic “lower Cedarville series” of Russell, now known to be Eocene, is part of an early continental-margin arc that ended southward in northwestern Nevada (Christiansen and Yeats, 1992); the “upper Cedarville series” of Russell, 32–17 Ma (Duffield and McKee, 1986), is a southeastward continuation of the mid-Tertiary arc designated in Oregon as the Western Cascades.

Basalts, mainly late Miocene but as young as Quaternary, mantle the Modoc Plateau and much of the region between the Warner Mountains and the Cascade Range (McKee et al., 1983; Duffield and McKee, 1986). The Quaternary Medicine Lake volcanic shield and caldera adjacent to the Cascades is predominantly mafic with lesser amounts of silicic lavas (Anderson, 1941; Donnelly-Nolan, 1988); Holocene rhyolite erupted high on the shield, and Holocene basalt is extensive on its flanks (Anderson, 1933a; Heiken 1978; Donnelly-Nolan et al., 1990).

The southern High Cascades arc, younger than about 7 Ma, extends from Oregon to south of Lassen Peak. Patterns of volcanic vents and faults are strongly influenced by basement structures and crustal properties (Blakely et al., 1997). Mount Shasta, the largest stratocone of the Cascades (it has nearly double the volume of Mount Rainier although it has a summit elevation about 250 feet lower), represents 600 k.y. of episodic cone building (Williams, 1934; Miller, 1980; Christiansen, 1982); an ancestral cone was largely destroyed by sector collapse about 300 ka (Crandell, 1989). A nearly continuous chain of mafic shields is broken by a gap of about 50 km between the Shasta and Lassen areas (Guffanti and Weaver, 1988). In the south, the oldest High Cascades eruptions produced volcanic debris-flow deposits of the Tuscan Formation, mainly about 2.5–3.5 Ma (Anderson, 1933b;

Harwood et al., 1981), that interfinger with several volcanic centers (Lydon, 1968) and include rhyolitic ash-flow tuff that once covered most of the Sacramento Valley (Anderson and Russell, 1939; Sarna-Wojcicki, 1976). The southernmost active center of the High Cascades is the cluster of late Quaternary dacitic domes, including Lassen Peak, on the eroded flank of the 600–400 ka Brokeoff stratovolcano (Williams, 1929b, 1932b; Clynne, 1990).

Volcanic rocks of the southern Cascades, Modoc Plateau, and adjacent parts of the Great Basin were reviewed by Macdonald (1966).

Sierra Nevada

Rhyolitic sediments and lavas, mainly of 23–21 Ma, occupy former west-flowing drainages in the northern and central Sierra Nevada (Piper et al., 1939; Dalrymple, 1964; Durrell, 1987) that headed farther east during a 28–22 Ma period of voluminous rhyolitic ash-flow eruptions in western Nevada (Slemmons, 1966). High in the Sierra, the rhyolites include several 28–21 Ma welded ash-flow tuffs that originated from sources farther east (Dalrymple, 1963, 1964; Deino, 1994).

During the middle to late Miocene, intermediate calc-alkalic magmas erupted in eastern California and western Nevada, many of them as eruptive and debris-flow breccias (Piper et al., 1939; Curtis, 1954; Chesterman, 1968; Gilbert et al., 1968; Durrell, 1987) that repeatedly filled the Sierran drainages before the range was uplifted and separated from the Great Basin (Bateman and Wahrhaftig, 1966). The source volcanoes, mainly older than 9 Ma, erupted near the present range crest and farther east (Slemmons, 1966), but a few dacitic domes occur in the western foothills (Rose, 1959). These predominantly andesitic volcanic rocks are parts of a mid-Miocene arc that extended southward through eastern California and western Nevada to about the latitude of Las Vegas (Christiansen and Yeats, 1992).

Latitic to basaltic 11–9 Ma lavas and ash flows, including a caldera center, occur high in the mid-Miocene arc sequence of the central Sierra Nevada (Dalrymple, 1963, 1964; Slemmons, 1966; Gilbert et al., 1968; Noble et al., 1974). Young volcanic rocks from the northern Sierra Nevada southward to about Sonora Pass, Bodie Hills, and Mono Lake include small areas of 8–3 Ma basalt, trachyandesite, and rhyolite (Dalrymple, 1964; Thompson and White, 1964; Chesterman, 1968; Gilbert et al., 1968; Silberman and Chesterman, 1972).

A notable contribution from the Berkeley group was the recognition by C. M. Gilbert (1938) of voluminous, mainly welded rhyolitic ash flows, the Bishop Tuff, east of the Sierran front. The source of the tuff is the Long Valley caldera, 30 km across (Bailey et al., 1976; Bailey, 1989). By 1.1 Ma rhyolitic magma had filled a large chamber (Metz and Mahood, 1985) that was disrupted at 760 ka by eruption of the 700 km³ Bishop Tuff (Dalrymple et al., 1965; Bailey et al., 1976; Hildreth, 1979; Wilson and Hildreth, 1997), depositing fallout ash over much of the western United States (Izett et al., 1970). The rhyolitic Inyo and Mono domes and flows, younger than 30 ka, extend 50 km north-

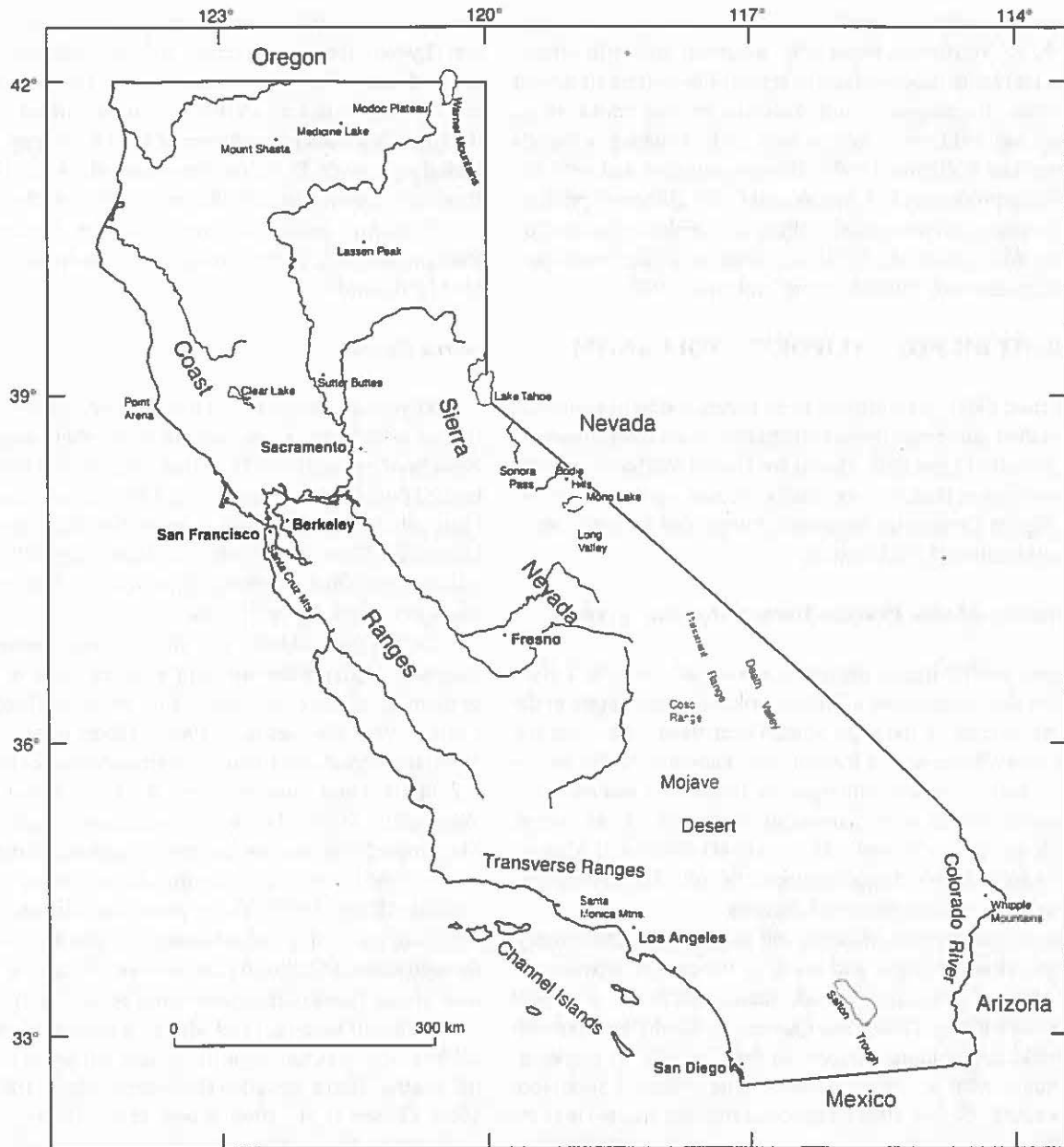


Figure 1. Map of California showing major localities mentioned in the text.

ward from the caldera to Mono Lake (Dalrymple, 1967; Bailey et al., 1976; Wood, 1977); their most recent eruptions were about 600 years ago (Miller, 1985; Sieh and Bursik, 1986). Since 1980, intense seismicity, uplift, and CO_2 emissions have signaled continuing activity of the Long Valley magmatic system (Hill, 1996).

California deserts

Miocene and younger volcanism between the southern Sierra Nevada and central Death Valley produced bimodal assemblages of basalt-trachyandesite and rhyolite. An area near the north end of Death Valley is pocked by basaltic Holocene maar volcanoes

(Crowe and Fisher, 1973). In the Coso Range, bimodal volcanism has been especially intense since about 6 Ma (Duffield et al., 1980; Bacon et al., 1980), and the youngest eruptions are roughly time predictable from the volume of the preceding eruption (Bacon, 1982).

In the central Mojave Desert region, ca. 25–22 Ma volcanic and sedimentary rocks are generally dominated by andesite and are overlain by 20–17 Ma basalts and silicic tuffs from local centers. The Peach Springs Tuff, a distinctive and voluminous 18 Ma rhyolitic ash-flow sheet, extends from the western Colorado Plateau to the central Mojave Desert (Young and Brennan, 1974; Nielson et al., 1990). Middle and upper Miocene andesites and

dacites from Death Valley to the northern Mojave Desert (Dibblee, 1967; Smith, 1964) may be parts of the mid-Miocene arc, but a gap in the arc extends southward from the central Mojave and southern Nevada to beyond the Mexican border, marking initiation of a transform boundary between the Pacific and North America plates. Local 10 Ma and younger basalts to basanites, commonly with conspicuous ultramafic mantle inclusions, dot the Mojave region (Parker, 1963; Wise, 1969; Dohrenwend et al., 1984; Farmer et al., 1995).

In a corridor of highly extended upper crustal rocks along the lower Colorado River, magmatism generally followed the 25–26 Ma earliest dated local extension, although in the Whipple Mountains (Davis et al., 1980), andesite and basalt of 32–26 Ma that predate detachment faulting are overlain by 19–17 Ma synextensional andesite. Early to middle Miocene calc-alkalic volcanism in this corridor was succeeded by later Miocene basalts and bimodal rhyolite-basalt fields associated with regionally distributed basin-range faulting (Crowe, 1978).

The Gulf of California oceanic spreading center penetrates the continent at the Salton Trough. Small-volume volcanism (Robinson et al., 1976) associated with opening of the Gulf of California since about 4–5 Ma produced rhyolite domes as well as tholeiitic basalts that occur as inclusions in the rhyolite and as subsurface sills, dikes, and flows. The magmatism sustains several high-temperature geothermal systems that are actively metamorphosing the sedimentary fill of the Salton trough (Muffler and White, 1969).

Coastal California

Two lower Miocene, dominantly silicic or bimodal volcanic fields at the western margin of the California desert area are offset more than 300 km northwest along the San Andreas fault system (Dibblee, 1967; Turner, 1970; Crowell, 1973; Matthews, 1976; Frizzell and Weigand, 1993; Sims, 1993). Late Oligocene to early Miocene volcanism also produced dacitic volcanic and shallow intrusive rocks in the southern Coast Ranges (Ernst and Hall, 1974) and submarine lavas in the Santa Cruz Mountains and near Point Arena (Turner, 1970; Fox et al., 1985). Restoring mid-Miocene and younger right slip places these volcanic rocks between the paleolatitudes of Las Vegas and Tucson, suggesting that they were initially parts of a continuous largely rhyolitic mid-Tertiary magmatic belt across the southern basin-range region (Christiansen and Yeats, 1992). Dickinson (1997), however, related them to mantle upwelling that occurred as the Pacific plate initially encountered North America to end subduction of part of the Vancouver-Farallon plate.

Predominantly intermediate ca. 20–12 Ma calc-alkalic rocks are widespread in coastal southern California, some of them interlayered in marine sedimentary rocks, including in the Los Angeles basin (Woodring et al., 1946; Shelton, 1955; Yerkes, 1957; Schleicher, 1974; Weigand, 1982), the western Transverse Ranges (Yerkes and Campbell, 1979; Weigand, 1982; Weigand and Savage, 1993), the northern Channel Islands (Crowe et al., 1976; Vedder et al., 1979), and near the Mexican border

(Hawkins, 1970; Gastil et al., 1979). Volcanic-arc rocks of 24–8 Ma on both sides of the Gulf of California (Gastil et al., 1979; Sawlan and Smith, 1984), separated as much as 480 km by oceanic spreading since 5 Ma, are relatively little rotated. By contrast, the northern Channel Islands and Santa Monica Mountains are laterally disrupted and may have been rotated 70°–130° clockwise since the mid-Miocene (Luyendyk et al., 1985). Restoration would make mid-Miocene andesitic rocks of southern California contiguous with the continental-margin arc in northwestern Mexico, south of the transform-related gap (Christiansen and Yeats, 1992), although Dickinson (1997) related them to a second pulse of mantle upwelling following a rise-trench encounter that ended subduction of the Monterey-Arguello plate.

With widening of the subduction gap and northward retreat of the southern termination of the arc since about 15 Ma, large magmatic systems have propagated northward through the central Coast Ranges, lagging migration of the Mendocino triple junction by about 80–100 km (Dickinson and Snyder, 1979; Weigand, 1982; Fox et al., 1985; Dickinson, 1997). The youngest of these is the basaltic to rhyolitic Clear Lake volcanic field of 2 Ma to 10 ka (Anderson, 1936; Hearn et al., 1981, 1995). The important geothermal field at the Geysers is sustained by heat from this magmatic system. To the east, rhyolitic domes of the Pleistocene Sutter Buttes and contemporaneous buried intrusives (Williams and Curtis, 1977) were emplaced during a wave of tectonic deformation in the Sacramento Valley as the Mendocino triple junction passed offshore (Harwood and Helley, 1987).

Small-volume basaltic or bimodal magmatism has occurred intermittently since the early Miocene along the lengthening coastal transform fault system, including the California Continental Borderland (Hawkins et al., 1971), the southern Coast Ranges and westernmost Transverse ranges (Vedder, 1975; Hall, 1981), and the San Francisco Bay area (Fox et al., 1985; McLaughlin et al., 1996).

PERSPECTIVE

Studies of volcanism and volcanic rocks in California have advanced considerably in the past few decades. It is important to note, however, that the conceptual advances are built upon a foundation of detailed and systematic geologic mapping, stratigraphic study, geochronology, petrologic investigation, and volcanological interpretation of individual volcanic areas. Such intensive studies were pioneered in California by Howel Williams and a notable group that he influenced during his long tenure at the University of California at Berkeley. Great strides taken since then follow paths laid out in those first modern approaches to problems of California volcanism.

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