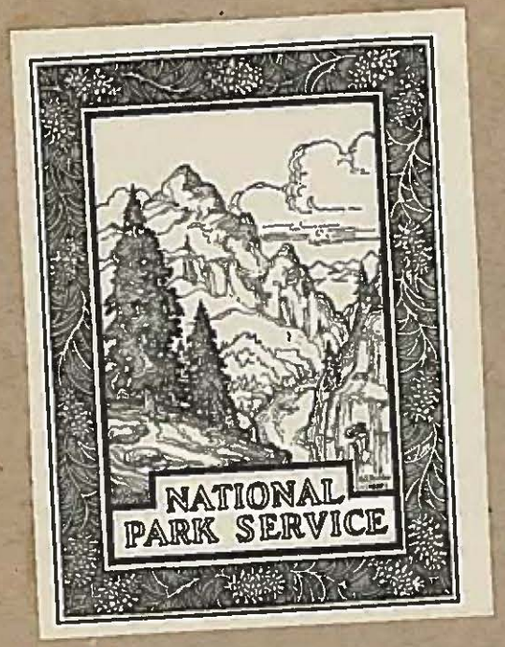
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LASSEN VOLCANIC NATIONAL PARK,
MINERAL CALIF.

THE TUSCAN FORMATION OF NORTHERN CALIFORNIA

WITH A DISCUSSION CONCERNING THE ORIGIN OF VOLCANIC BRECCIAS

BY

CHARLES A. ANDERSON

UNIVERSITY OF CALIFORNIA PUBLICATIONS
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CALIF.
MINERAL

THE TUSCAN FORMATION OF NORTHERN CALIFORNIA WITH A DISCUSSION CONCERNING THE ORIGIN OF VOLCANIC BRECCIAS

BY
CHARLES A. ANDERSON

INTRODUCTION

The Tuscan formation is continuously exposed for a distance of 65 miles along the east side of the Sacramento Valley, California, extending from Pentz, 8 miles north of Oroville, to Battle Creek, 15 miles north of Red Bluff. (See fig. 1). Smaller areas are exposed to the east of Redding, where they are covered in part by later lava flows and sediments. The alluvium and Pleistocene gravels (Red Bluff formation) of the Sacramento Valley comprise the western border, while later lava flows and ridges of older rocks limit the eastern exposures.

This formation appears at the southern end of the volcanic province commonly referred to as the Cascade Range (fig. 2), while the older rocks to the east are part of the Sierra Nevada. To the west, the volcanic Tuscan formation interdigitates with the Tehama formation (essentially non-volcanic), which forms a part of the Coast Range.

Two and one-half months were devoted to field study during the summer of 1929 and subsequent laboratory work was carried on at the University of California. In the short time devoted to field study, it was impossible to cover all the exposed area of the Tuscan formation, and for that reason certain areas were selected where it was thought that detailed studies would yield desirable evidence. A number of critical sections were also measured at various localities.

ACKNOWLEDGMENTS

The writer is indebted to Mr. R. H. Finch, of the United States Geological Survey Volcanological Observatory at Mineral, California, for suggesting the problem and for providing some financial assistance for the field work. Professor N. E. A. Hinds, of the University of California, and Dr. R. D. Russell, of Louisiana State University, spent several days in the field with the writer and their discussions of the field evidence have been most helpful. Professor Howel Williams has contributed much valuable information regarding the geology of the Lassen Peak region and has taken part in many welcome discussions regarding the problems related to the Tuscan formation. The writer wishes to thank Professor

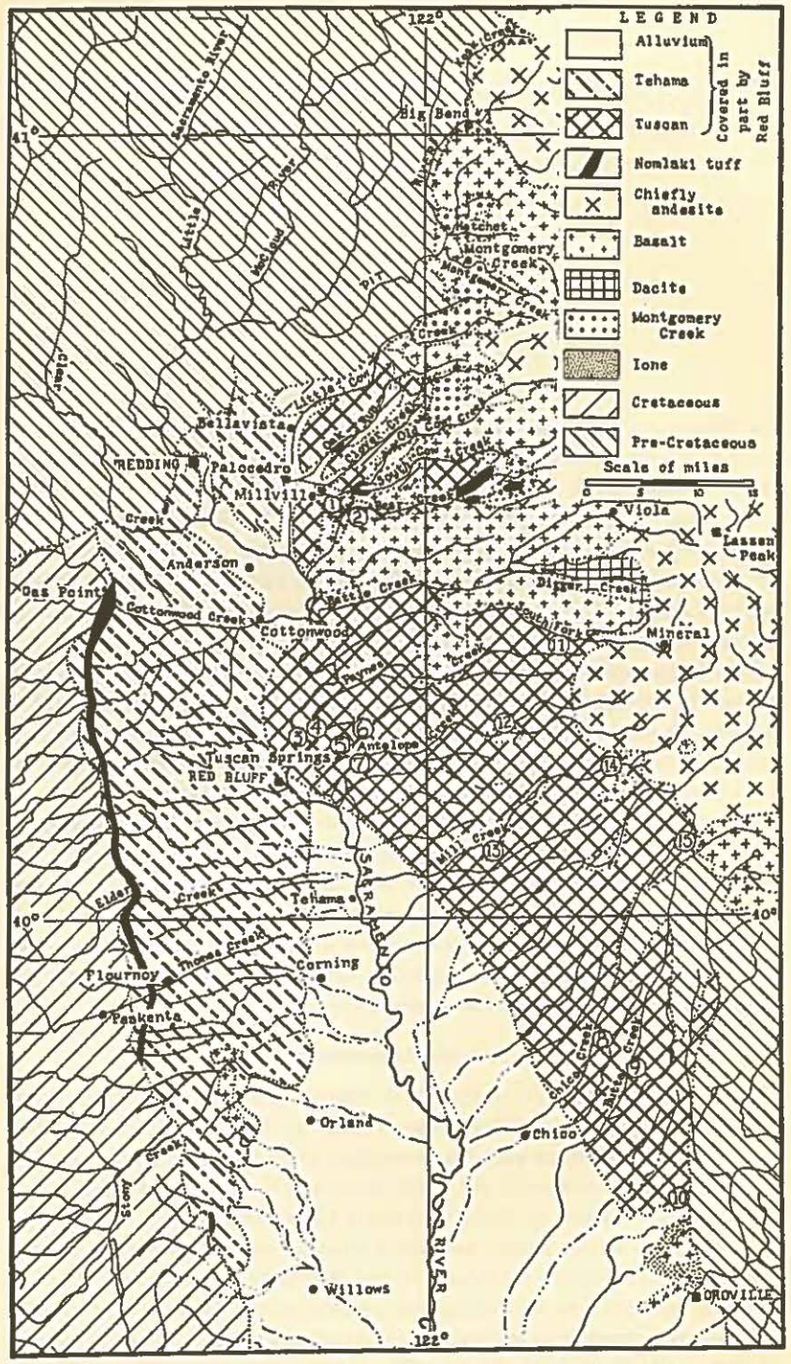


Fig. 1. Geologic map of a portion of northern California. See figure 2 for position. The numbers refer to sections shown in figure 3.

G. D. Louderback for specimens from Iron Canyon and to acknowledge several fruitful discussions. Mr. F. A. Johnson has assisted the writer in the preparation of the mechanical analyses of the clastic rocks. To Mr. S. D. Furber, of Red Bluff, the writer wishes to express his appreciation for information regarding the location of several important sections.

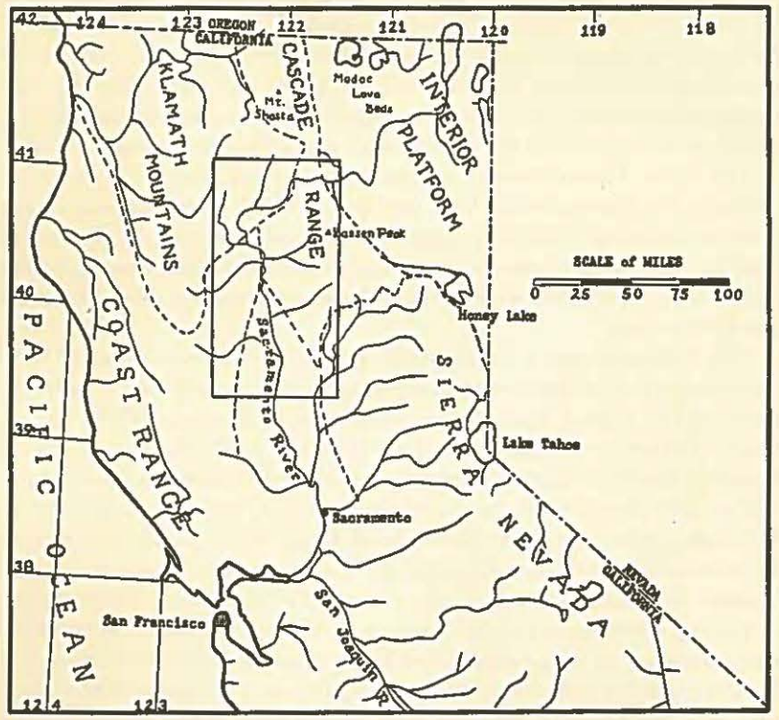


Fig. 2. Index map of northern California outlining the various mountain ranges (after Diller, 1894, pl. 40) and locating figure 1 which shows some of the details of the geology on a larger scale.

PREVIOUS LITERATURE

One of the earliest references to the Tuscan formation appears in the report of the Geological Survey of California (Whitney, 1865, p. 206). It was noted therein that ash beds overlie the Cretaceous shales and sandstones at Tuscan Springs, while the rocks in the upper part of the exposed section were referred to as basaltic lava.

For most of our information regarding the Tuscan formation we are indebted to Diller. In his first description (1889, p. 422) he referred to the formation as a series of volcanic agglomerates, tuffs, and conglomerates of Pliocene age consisting chiefly of fragments of hypersthene

andesite, although fragments of hornblende andesite and basalt are common. In the canyons of Mill Creek and Deer Creek (fig. 1), he found that the tuff, as he termed the formation, has a thickness of nearly 1000 feet, with much of the material sorted and stratified. Rounded pebbles and sand indicate considerable water abrasion, and he suggested that the body of water in which they were laid down filled the northern end of the Sacramento Valley. Part of the assorted material he regarded as having been ejected during violent volcanic eruptions and carried for considerable distances by winds before falling into the water. He also made the statement that intercalated lava flows are not uncommon. No evidence was presented for the Pliocene age of the formation.

The name Tuscan formation was applied to this series of rocks by Diller in the Lassen Peak Folio (prelim. ed., 1892; 1895) because of the good exposures at Tuscan Springs. In a short note describing the formation, he stated that it was composed of soft sandy or pebbly rocks, called tuff, whose fragments were derived from numerous extinct volcanoes toward the east.

In a following paper Diller (1894, p. 412) was more concerned with the distribution of these rocks and pointed out that the greatest development of the Tuscan formation is along the eastern side of the Sacramento Valley extending from the Pit River to Pentz, just north of Oroville. He also referred to exposures of a reddish to white fine-grained tuff on the west side of the Sacramento Valley, from 35 to 50 feet in thickness, extending from Cottonwood Creek south to Thomes Creek. Because of the westward thinning he concluded that the source of the Tuscan formation was among the volcanoes of the Lassen Peak region.

Turner (1896, pp. 540–542) gave an excellent description of the Tuscan formation as it appears in the Chico area, in which he referred to it as the Tuscan tuff rather than as the Tuscan formation. The resemblance of the Tuscan formation, in a general way, to the andesitic tuffs and breccias in the region south of the North Fork of the Feather River was noted by Turner, but his studies showed that the material in the Chico area is chiefly basaltic and he believed that it came originally from vents in the Lassen Peak volcanic region. Turner concluded his discussion by remarking that he thought that the andesitic tuff series, so extensively developed in the central part of the Sierra Nevada, is older than a great portion of the Tuscan formation, a view supported by the present study.

In the description of the Tuscan formation as it occurs in the Redding quadrangle, Diller (1906) used the term Tuscan tuff, but mentioned that it ranges from "coarse agglomerates, in which there are unassorted angular fragments a yard in diameter mingled with fragments of all sizes, down to dust. Fine-textured gray tuff, often distinctly stratified, is by far the most abundant." He determined most of the material as

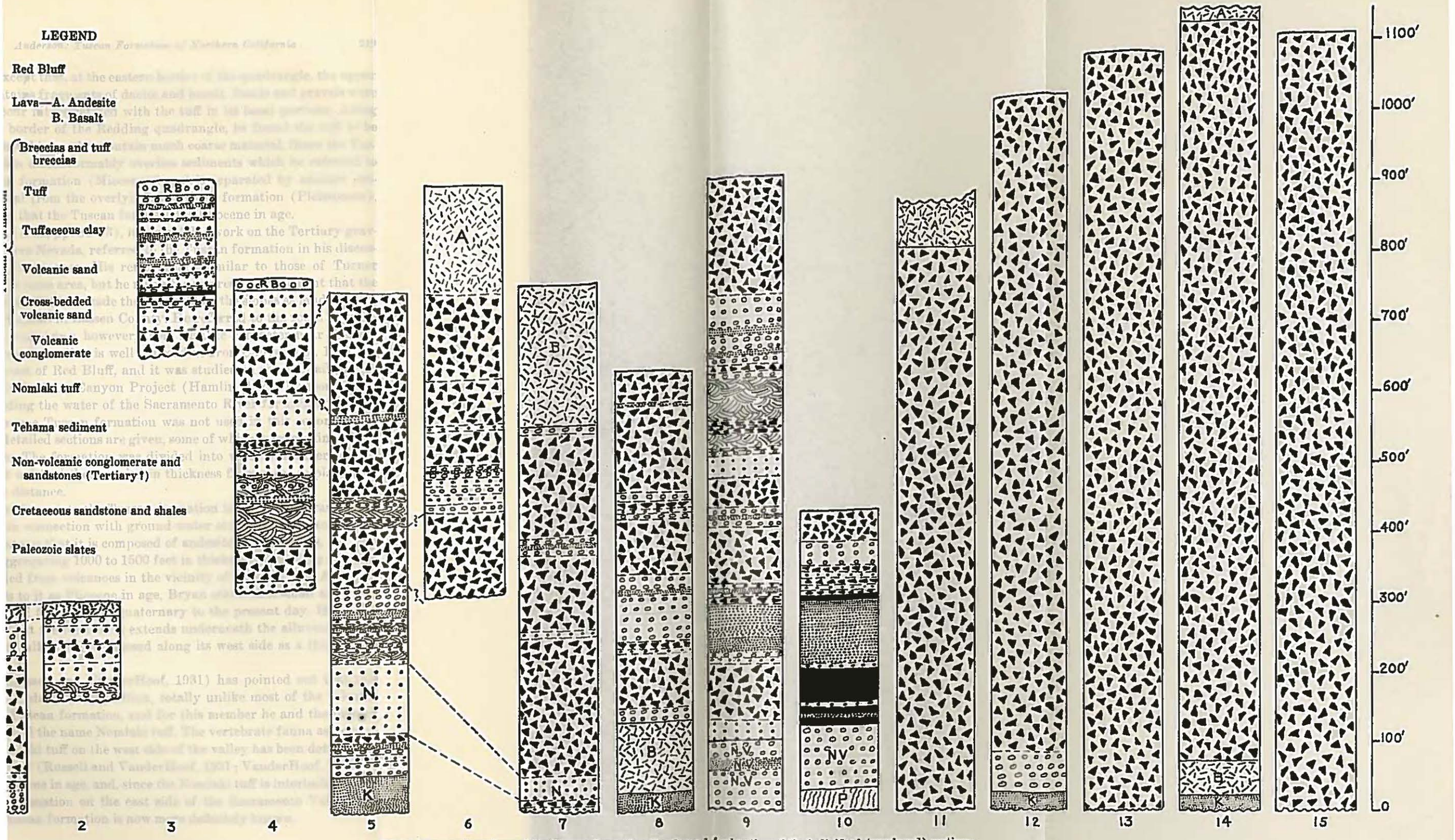


Fig. 3. Measured sections of the Tuscan formation. See figure 1 for location of the individual (numbered) sections.

1. South Cow Creek
2. Bear Creek
3. Big Bend, Sacramento River
4. Iron Canyon, Sacramento River
5. Tuscan Springs
6. Tuscan Buttes
7. Antelope Creek
8. Chico Creek
9. Butte Creek
10. Welch's Hydraulic Mine, north of Oroville
11. South Fork of Battle Creek
12. Antelope Creek
13. Mill Creek
14. Mill Creek
15. Chico Creek

andesitic, except that, at the eastern border of the quadrangle, the upper portion contains fragments of dacite and basalt. Sands and gravels were stated to occur interstratified with the tuff in its basal portions. Along the eastern border of the Redding quadrangle, he found the tuff to be about 400 feet thick and to contain much coarse material. Since the Tuscan formation disconformably overlies sediments which he referred to as the "Ione formation (Miocene)" and is separated by another erosional interval from the overlying Red Bluff formation (Pleistocene), he concluded that the Tuscan formation is Pliocene in age.

Lindgren (1911, pp. 84–93), in his notable work on the Tertiary gravels of the Sierra Nevada, referred to the Tuscan formation in his discussion of the Chico area. His remarks are similar to those of Turner regarding the same area, but he made the interesting statement that the enormous masses of tuff made their way down the slopes as mud streams from the volcanoes in Lassen County. He referred to the rocks as andesitic tuffs, recognizing, however, their basaltic character near the top.

The Tuscan formation is well exposed at Iron Canyon (pl. 19*a*), six miles northeast of Red Bluff, and it was studied in some detail in connection with the Iron Canyon Project (Hamlin, 1920; Lawson, 1920) for impounding the water of the Sacramento River for irrigation purposes. The name Tuscan formation was not used in this report, but a number of detailed sections are given, some of which were obtained from drill records. The formation was divided into various members and it was brought out that these varied in thickness from place to place even over a short distance.

Another reference to the Tuscan formation is given by Bryan (1923, pp. 72–73) in connection with ground-water studies of the Sacramento Valley. He states that it is composed of andesite lava, breccias, and volcanic ash aggregating 1000 to 1500 feet in thickness, consisting of materials extruded from volcanoes in the vicinity of Lassen Peak. Although Diller refers to it as Pliocene in age, Bryan states that small eruptions have continued through the Quaternary to the present day. He agrees with Diller that the formation extends underneath the alluvium of the Sacramento Valley and is exposed along its west side as a thin bed of pinkish tuff.

Russell (Russell and VanderHoof, 1931) has pointed out that this pink tuff is of dacitic composition, totally unlike most of the volcanic tuffs of the Tuscan formation, and for this member he and the present writer proposed the name Nomlaki tuff. The vertebrate fauna associated with the Nomlaki tuff on the west side of the valley has been determined by VanderHoof (Russell and VanderHoof, 1931; VanderHoof, 1933) to be Upper Pliocene in age, and, since the Nomlaki tuff is interbedded with the Tuscan formation on the east side of the Sacramento Valley, the age of the Tuscan formation is now more definitely known.

NOMENCLATURE

It is unfortunate that there appears to be no uniformity in geological nomenclature regarding the description of pyroclastic rocks. This is strikingly shown in the terms volcanic breccia, volcanic conglomerate, and agglomerate—terms that have been used by various writers to describe the rocks of the Tuscan formation. For this reason it appears desirable to review a few of the definitions that have been applied and to define and illustrate their use in this paper.

Lyell (1839, p. 98) defined a volcanic breccia as follows:

> Small angular fragments of scoria, pumice, dust, produced by volcanic explosions, form the tuffs..... When fragments are coarse, the rock is styled a volcanic breccia.

Later he added the term agglomerate, differentiating between the two merely on the size of the fragments (Lyell, 1855, pp. 475–476).

> Term volcanic breccia may be restricted to those tuffs which are made up of small angular pieces of rock..... Agglomerate—a coarse breccia, composed of fragments or rock cast out of volcanic vents, for the most part angular, without admixtures of waterworn stones.

Geikie (1882, p. 163) suggested at one time that agglomerates be limited to fragmental rocks in volcanic vents.

> Volcanic agglomerate. A tumultuous assemblage of blocks of all sizes up to masses several yards in diameter, met with in "necks" or pipes of old volcanic orifices.

Pirsson (1915, p. 192) has advocated this limited definition. Later Geikie (1897, p. 31) distinguished between the two upon the basis of stratification.

> The coarser fragmentary materials thrown from volcanic vents are known as Agglomerates where they show no definite arrangement, and especially where they actually fill up the old funnels of discharge. When they have accumulated in sheets or strata of angular detritus outside an active vent they are termed Breccias or if their component stones have been water-worn, Conglomerates. The finer ejected materials may be comprehended under the general name of tuffs.

Lacroix (1906) does not use the term agglomerate in his valuable study of volcanic breccias and conglomerates but defines the latter two as follows:

> I shall reserve the term breccia for those formations rich in blocks, produced *a sec* and the term conglomerate for those produced *par voie aqueuse*.

In other words, a deposit of angular fragments produced by water action, he would refer to as a conglomerate. But, as he points out, the origin of breccias and conglomerates, in the sense in which he uses these terms, is complex and susceptible of many solutions, and the use of the term breccia or conglomerate would depend upon the individual interpretation of a deposit.

Williams (1926, pp. 234–235) has reviewed the classification of pyroclastic rocks and has advocated the following definitions:

Volcanic Agglomerates. Contemporaneous, coarse pyroclastic rocks containing an abundance of large, chiefly rounded or subangular fragments. When localized inside the volcanic necks, they may be specialised as *vent-agglomerates*..... *Volcanic Breccias.* Coarse pyroclastic rocks containing an abundance of large, chiefly angular fragments. They may be partly sedimentary or purely pyroclastic, contemporaneous or non-contemporaneous..... *Volcanic Conglomerates.* Sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded and water-worn fragments.

In the established nomenclature of sedimentary rocks (Löwinson-Lessing, 1888, pp. 533–534; Norton, 1917, p. 160; Reynolds, 1928, p. 97) the term breccia connotes a rock composed of coarse angular fragments while conglomerates are distinguished by the rounded form of the fragments, brought about by considerable abrasion, and for this reason it appears that Lacroix's use of the term volcanic conglomerate is misleading.

Since the accumulation of breccias, conglomerates, and tuffs has been given the comprehensive stratigraphic name of Tuscan tuff, it might be well to consider briefly the use of the term tuff. Williams (1926, pp. 224–232) has given an excellent historical review and suggested

that the term tuff be confined to all the compacted, finer fragmentary ejecta of volcanoes, whether pure or sedimentary. Although the limiting size of tuff fragments has never been accurately defined, they rarely exceed a quarter of an inch in average dimension.

For the distinction between tuff and breccia, Pirsson (1915, p. 193) made the following statement:

Fragmental volcanic material may be roughly divided for convenience into pieces the size of an apple and upward as *volcanic bombs;* those the size of nuts, *lapilli;* ones like small peas or shot, *volcanic ashes;* while the finest is *volcanic dust.* The divisional points may be supposed to lie midway between these sizes. The coarser material, the bombs, lapilli, and much of the ash, may fall around and near the vent and produce beds of *breccia;* the lighter ashes and dust, supported and carried by air currents, tend to fall after these and at greater and greater distances from the vent; their compacted material is known as *tuff.*

Bailey (1926, p. 108) made the apt statement that definitions based upon the size of nuts, apples, and peas are unsatisfactory, because of their variation in size. He proposed a classification adapted from Udden's (1914) classification of clastic sediments, and this has the advantage of establishing definite size limits for the various grades of pyroclastic rocks. For example, where more than 50 per cent of the fragments range in size from 1 to 4 mm., Bailey would classify the rock as a fine volcanic breccia; if the material has been transported and redeposited by water, the rock would be a fine volcanic conglomerate. Between one-sixteenth and one mm., Bailey would classify the pyroclastic material

as very fine to coarse sand-tuff, and the water-transported material as very fine to coarse tuffaceous sandstone. Below one-sixteenth mm. the rocks would be dust or mud tuff and tuffaceous shale or clay.

Because of the variation of opinion regarding the definition of an agglomerate, the writer is reluctant to use the term, particularly since no vent accumulations and no contemporaneous deposits of rounded or subangular fragments were encountered in the study of the Tuscan formation. In this reluctance he is encouraged by the recent work of Wentworth and Williams (1932), who have prepared a classification and terminology of pyroclastic rocks under the auspices of the National Research Council, Committee on Sedimentation. Since the purpose of their paper is to establish a standard nomenclature for pyroclastic rocks, it appears desirable to follow their definitions, which the writer will do in this paper. Their definition of agglomerate is similar to that of Williams (1926), quoted on page 221.

A breccia is defined as follows:

> More or less indurated pyroclastic rocks consisting chiefly of angular ejecta 32 mm. or more in diameter.

Norton (1928, p. 160) has suggested the term tuff breccia for fragmental products of explosive eruptions where the matrix consists of the finer materials of the eruption, and Wentworth and Williams have adopted this term, which is also to be used in this paper. Illustrations of breccias and tuff breccias appear in plate 17*a*, *b*.

The following definitions will also be adopted from Wentworth and Williams:

> *Blocks.* These are chiefly fragments of accessory or accidental material, usually angular, and larger than 32 mm. (1¼ in.) in diameter, erupted in a solid state.
>
> *Lapilli.* Essential, accessory, and accidental ejecta ranging mostly from 32 to 4 mm. in diameter.
>
> *Lapilli tuff.* An indurated deposit essentially made up of lapilli in a fine tuff matrix.
>
> *Tuff.* Indurated pyroclastic rocks of grain generally finer than 4 mm., i.e., the indurated equivalent of volcanic ash or dust [pl. 17*d*]. If the grain is from 4 to 1 mm., aggregate is coarse ash, indurated, coarse tuff. If the grain is from 1 to ¼ mm., aggregate is medium ash, indurated, medium tuff. If the grain is less than ¼ mm., the aggregate is fine ash, indurated, fine tuff. Admixtures of clay and very fine ash will be designated as tuffaceous clay.
>
> *Volcanic gravel and volcanic sand.* Unconsolidated sediments containing an admixture of volcanic detritus [pl. 18*a*].
>
> *Volcanic conglomerate.* Sedimentary, coarse pyroclastic material containing an abundance of large, chiefly rounded and water-worn fragments [pl. 17*c*].

TUSCAN FORMATION

For many years the Tuscan formation has been known as the Tuscan tuff, but the series of rocks consists predominantly of tuff breccias with associated volcanic conglomerates, volcanic sands, coarse to fine tuffs, and tuffaceous clays. Since the amount of tuff is small (see fig. 3) it does not appear desirable to use it as a stratigraphic term, but to use the term "formation" as given by Diller (1895).

The eastern part of the exposed area of the Tuscan formation consists entirely of tuff breccias, averaging about 1000 feet in thickness. This is probably a minimum thickness in many places, for erosion has undoubtedly removed appreciable amounts where some of the sections were measured. These breccias, although massive in detail, are in distinct beds ranging from 40 to 100 feet in thickness, and are differentially etched by erosion (pl. 18*c*). At some places the individual beds are separated by overhanging cliffs (pl. 17*a*), and again there may be a distinct bench. Various beds of the tuff breccias extend to the west as far as the Sacramento River.

Toward the western margin of the exposed area, interbedded volcanic conglomerates appear (pl. 17*c*), frequently with a disconformable relationship to the underlying breccias. In good exposures, the filling of small stream channels by volcanic conglomerates may be seen. The most easterly exposure of conglomerate noted is along Antelope Creek (fig 3, no. 12), where it forms a bed 60 feet thick separating the overlying tuff breccias from the underlying Chico (Upper Cretaceous) sandy shales and shales. Some of the boulders in this conglomerate have a diameter of two feet, but the average diameter is from eight to ten inches. No sandy lenses were observed in this exposure.

Farther to the west, the volcanic conglomerate is more uniformly distributed, attaining greater thickness in Butte Creek, Chico Creek, and at Tuscan Springs. Several miles west of section 13 (fig. 1), three feet of volcanic cobble conglomerate with one foot of sandy lenses were noted interbedded with the tuff breccias near the top of the section.

Along the western margin, volcanic sands and tuffs become increasingly important (see fig. 3). They are usually present in thin beds, ranging from one to ten feet in thickness (pl. 19*a*). These volcanic fine clastics are usually bluish to purplish gray and yellow, in part massive and in part stratified. Five miles north of Red Bluff at the Big Bend of the Sacramento River, very fine tuffs and tuffaceous clays make up the major part of the section.

Since the various types of rocks present in the Tuscan formation are well exposed at Tuscan Springs and this has been designated as the type section by Diller (1895), it is desirable to give a detailed section as meas-

ured by the writer on the north bank of Salt Creek where the stream leaves the amphitheater of Tuscan Springs (Tehama quadrangle).

	Feet
Tuff breccia	175
Fine tuff, sandy appearance	10
Tuff breccia, cliff-forming	100
Cross-bedded volcanic sand with intercalated volcanic conglomerate	25
Lapilli tuff	5
Cross-bedded volcanic sand	10
Tuff breccia, cliff-forming	90
Volcanic conglomerate with boulders near the top	25
Stratified volcanic sand, pebbles, and cobbles appearing near the top	25
Coarse tuff with decomposed plant stems	2
Massive medium tuff	5
Cross-bedded volcanic sand	6
Fine blue-gray tuff	8
Volcanic sand	1
Massive coarse tuff with decomposed plant stems	1
Volcanic sand with scattered pebbles	5
Medium blue-gray tuff	6
Cross-bedded volcanic sand with intercalated conglomerate	10
Fine purple-gray tuff	2
Cross-bedded volcanic sand with scattered pebbles and cobbles	5
Compact fine white tuff	3
Cross-bedded volcanic sand with small lenses of conglomerate	10
Medium blue-gray tuff	5
White vitric-crystal hornblende-hypersthene dacite tuff	100
Scattered pumice fragments from ½ to 4 inches in dimension (Nomlaki tuff)	
Tuff breccia	15
Medium pale yellow tuff	5
Volcanic conglomerate with few non-volcanic pebbles	10
Medium blue tuff	10
Conglomerate with 50 per cent volcanic pebbles; 50 per cent chert, quartzite, quartz, etc., pebbles	20
Total thickness	694
Chico sandstones and shales	

A number of other sections were measured and these are shown in figure 3. The lenticular nature of the volcanic conglomerates, volcanic sands, and tuffs is seen by comparing adjacent sections, such as those of Iron Canyon (no. 4), Tuscan Springs (no. 5), Tuscan Buttes (no. 6), and Antelope Creek (no. 7). Hamlin (1920) has shown the same thing to be true on a much smaller scale at Iron Canyon where a number of sections were measured at close intervals.

VOLCANIC BRECCIAS AND TUFF BRECCIAS

In most of the tuff breccias, fragments larger than lapilli make up from 10 to 50 per cent of the rock (pl. 17*a*). There is a remarkable variation in the distribution of these blocks even over a short distance so that

locally a particular outcrop might be called a breccia (pl. 17*b*). Some quantitative data is supplied from the drill-core records at Table Mountain dam site along the Sacramento River where a series of cores were made in the tuff breccias (Louderback and Ransome, 1931). In these test holes the matrix was too soft to core, so that the drill records gave good estimates of the amount of blocks.

Test hole No. 1	58 feet of core	27 per cent blocks
Test hole No. 2	44 feet of core	13 per cent blocks
Test hole No. 3	55 feet of core	27 per cent blocks
Test hole No. 4	73 feet of core	38 per cent blocks
Test hole No. 5	84 feet of core	15 per cent blocks
or maybe	57 feet of core	21 per cent blocks

Holes numbers 3 and 4 each contained a single block, respectively 6.3 and 6.5 feet, which helped to raise the percentage of blocks. The average of these cores is approximately 25 per cent blocks.

Throughout the exposures of the tuff breccias, the blocks usually range in size from one to six inches. In particular beds, the average size of the blocks may range from two to three inches; in others it will be as high as four to six inches. Scattered blocks one to five feet in diameter are found without difficulty (pl. 19*b*), but usually they make up only a small portion of the rock. The largest block observed occurs in the tuff breccias at Table Mountain (northeast of Red Bluff). It has a length of 45 feet, a width of 20 feet, and a height of 12 feet. This particular block contained vesicles 3 inches long. Occasional flattening and alignment of the vesicles suggest that some of the blocks were derived from lava flows. Water-worn cobbles may appear in the tuff breccias, always in minor amount (pl. 18*b*).

Where there has been considerable erosion of the breccias, there is a marked concentration of the larger blocks upon the present surface, as rain wash and wind erosion have been unable to remove them. This results in stony plains (pl. 20*a*), which are so commonly developed on the lower slopes east of the Sacramento Valley. A false impression as to the quantity of large blocks in the tuff breccias is easily gained by traversing these more or less barren stony plains. In regions of higher elevation, a well developed soil mantle masks such blocks if they are present.

The surface of the tuff breccias is usually hard, so that hand specimens break through the lapilli enclosed in the matrix. In some specimens a well defined crust is present having a thickness of an inch or two. In thin section, it is seen that this crust is merely a superficial cementation of opal and ankerite, for tests of the carbonate indicate the presence of iron, magnesium, and calcium. A tunnel at Iron Canyon shows that the tuff breccias are moderately cemented for a distance of from eight to ten feet from the surface, but the rest of the tunnel is in loose crumbling material (Louderback and Ransome, 1931, p. A16).

In the walls of the stream canyons, pronounced cliffs may form from the tuff breccias. In some places, a large block or a more indurated bed may protect the underlying tuff breccias from erosion, and thus pillars are developed (pl. 21). Vertical jointing aids in the formation of these pillars, which are particularly well developed along the middle course of Battle Creek.

Petrographic character.—With the exception of the Nomlaki tuff and the Tuscan tuff breccias exposed east of Redding, the rocks comprising the breccias, tuff breccias, volcanic conglomerates, volcanic sands, and tuffs of the Tuscan formation are andesites and basalts, with the latter predominating. These basalts may be hypersthene augite olivine basalts, augite olivine basalts, or hypersthene augite basalts.

HYPERSTHENE AUGITE BASALT. Block in lower tuff breccia, Iron Canyon. Dark colored with small vesicles and conspicuous white plagioclase phenocrysts. Under the microscope, labradorite phenocrysts (An 60) from 1 to 1.5 mm. in length, weakly zoned with glass inclusions, are associated with scattered stubby hypersthene phenocrysts 0.75 mm. in length. The groundmass consists of plagioclase, pale gray augite, and hypersthene crystals with scattered magnetite cubes (all about .01 mm.) imbedded in a dark brown glassy base with abundant magnetite dust.

HYPERSTHENE AUGITE OLIVINE BASALT. Block associated with above specimen. Dark colored with abundant small vesicles. Abundant labradorite phenocrysts (An 62) ranging from 0.5 to 0.75 mm. in length. Greenish gray augite phenocrysts of the same size are present in smaller amount. Olivine (ranging from 0.1 to 0.7 mm.) is usually fresh although it is occasionally altered to pale green serpentine. Occasionally the olivine is rimmed by magnetite. Hypersthene, in slender prisms, occurs in subordinate amount. The groundmass consists of stubby plagioclase, augite, olivine, and hypersthene imbedded in a clear dark brown glass containing minute magnetite cubes.

HYPERSTHENE AUGITE BASALT. Block from tuff breccia, Big Butte Creek. Phenocrysts of labradorite (An 60), hypersthene, greenish gray augite, from 0.7 to 1 mm. in length, in a pilotaxitic groundmass of plagioclase and pyroxene microlites with numerous magnetite cubes.

AUGITE OLIVINE BASALT. Block in tuff breccia at Welch's Hydraulic Mine. Grayish black, faintly vesicular. Numerous olivine crystals, ranging from 0.1 to 1.0 mm. in dimension, are scattered through the slide. The larger olivine crystals are bordered with iddingsite, while the smaller crystals are completely altered. Sporadic greenish gray augite crystals 1 mm. in size occur as well as a few large labradorite crystals (An 62). The major part of the rock is composed of a holocrystalline aggregate of euhedral plagioclase crystals with interstitial granules of greenish gray augite (microdiabasic texture). Numerous magnetite cubes 0.1 mm. in size also lie between the plagioclase.

There is always some variation in individual specimens, but the above descriptions are typical. The amount of vesiculation may vary as well as the amount of chalcedonic filling. Frequently this secondary chalcedony has a pronounced pale blue color which may be quite conspicuous. The ratio of the femic minerals may vary; in many specimens olivine is abundant, in others only sporadic grains will appear in thin section. The alteration of the olivine also varies, changing to green serpentine in some places, but more commonly to iddingsite or possibly bowlingite. Hyper-

sthene is usually present in all specimens although varying in amount. It may occur as conspicuous phenocrysts or as small prisms in the groundmass; only in the microdiabasic variety is it likely to be absent. The plagioclase varies from acid bytownite to acid labradorite; some of the rocks containing labradorite might be classified as basic pyroxene andesites or andesitic basalts.

The groundmass varies from microdiabasic to hyalopilitic with many specimens exhibiting a pilotaxitic groundmass. In the hyalopilitic texture, the glass base may be clear brown to black opaque heavily charged with magnetite dust. In the latter state, the color of the rock is usually black, but, if the glass base is clear, the magnetite occurs as distinct crystals and the rock is usually gray to grayish black.

In a few specimens of basalt, scattered phenocrysts of hornblende, usually almost completely resorbed to magnetite, may be found, even where there is an appreciable content of olivine. This hornblende may be deep reddish brown basaltic hornblende or greenish brown hornblende, the former predominating.

The andesites occur only as sporadic blocks in the tuff breccias, although some of the minerals are found in the matrix in many places. However, in the middle of the section measured on Big Butte Creek, andesites make up an appreciable part in some of the beds of tuff breccia.

BIOTITE HORNBLENDE ANDESITE. Big Butte Creek. Pale gray rock with scattered slender biotite and green hornblende phenocrysts associated with andesine (An 35). Groundmass consists of microlites of plagioclase and biotite in a microgranular base (appears devitrified). Stubby apatite prisms are usually associated with the biotite.

HORNBLENDE ANDESITE. From tuff breccia, Big Butte Creek. Conspicuous white plagioclase and hornblende phenocrysts from 1 to 1.5 mm. in size imbedded in a reddish groundmass. Under the microscope, phenocrysts are seen to consist of andesine (An 36) and basaltic hornblende resorbed to iron oxide. Pilotaxitic groundmass of microlites of plagioclase and hornblende altered to red oxide.

PYROXENE HORNBLENDE ANDESITE. Red porphyritic lapilli in tuff breccia, Antelope Creek (section 12). Similar to the hornblende andesite described above except that deeply pleochroic hypersthene phenocrysts are present, also rimmed by iron oxide accompanied by small crystals of greenish augite. The hyalopilitic groundmass contains a greenish glass base irregularly stained with red iron oxide.

Variations occur in the andesites as in the basalts. They may be massive or vesicular. Pyroxene hornblende andesites are present in which the iron oxide borders of the hornblende and hypersthene are absent and the groundmass is usually colorless or greenish gray.

Matrix of tuff breccias.—The matrix of the tuff breccias consists of lapilli and coarse to fine ash. The lapilli are usually fragments of the rocks described above, while the ash is made up primarily of crystals with minor amounts of lithic material, the latter being composed chiefly of fragments of the groundmass of the basalts and andesites. The crystals and lithic fragments are always angular.

Crystals of plagioclase feldspar usually make up the major part of the matrix. These vary in composition from andesine to acid bytownite, but in large part are labradorite, medium to basic labradorite predominating. Where andesite blocks are numerous, there is an increase in the amount of andesine crystals, but these are always accompanied by labradorite. Hypersthene is ubiquitous, as well as greenish gray augite. Olivine crystals are more sporadic; in some thin sections they are absent, while in others they are abundant. Usually a very small percentage of reddish brown hornblende is present, but only in occasional specimens does green hornblende appear, except where blocks of hornblende andesite are important constituents. Magnetite crystals are always important minor constituents. Biotite is extremely rare, appreciable quantities being found only in some of the tuff breccias along Butte Creek. The matrix is frequently bound together by a small amount of montmorillonite. Other secondary minerals include ankerite, chlorite, serpentine, and opal.

TUFF BRECCIAS OF THE REDDING QUADRANGLE

This dominantly basaltic assemblage of the Tuscan formation south of Battle Creek is absent in the region east of Redding (fig. 1), where the formation becomes andesitic and dacitic, and contains only a sprinkling of basaltic detritus. An exception is the section measured on Bear Creek (fig. 3, no. 2), for here the basaltic character is important. In the South Cow Creek section (fig. 3, no. 1) the lower part of the section is andesitic with a trace of dacitic constituents, but near the top basaltic fragments are more common.

North of Bear and South Cow creeks, the Tuscan tuff breccias are thin, usually ranging from 40 to 60 feet in thickness, and represent merely a veneer over the underlying Tuscan and Tehama sediments (fig. 4). In these sediments non-volcanic detritus comprises the major part of the sands and conglomerates.

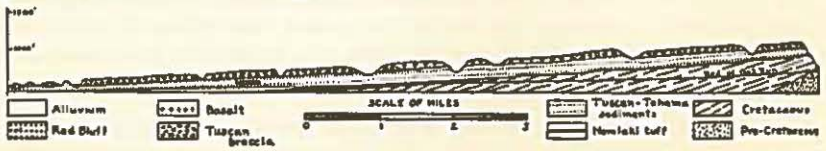


Fig. 4. Cross-section along Oak Run, east of Redding. From Russell (1931).

These thin coverings of tuff breccias were probably thicker, as they are always mantled with scattered blocks, indicating that considerable erosion has taken place. Compared with most of the tuff breccias to the south, these are always lighter colored, the matrix usually being buff colored as contrasted with the various shades of brown and gray that characterize the matrix of the southern breccias. Scattered pumice fragments similar to those in the underlying dacitic Nomlaki tuff are char-

acteristically present in nearly all exposures. The matrix of these breccias contains much plagioclase, ranging from basic oligoclase to labradorite, with andesine making up the major part. Augite and hypersthene are usually present in variable amounts, while olivine occurs only in sporadic specimens. Hornblende is much more common than in the tuff breccias to the south, both green and reddish brown varieties being present. Biotite is found in some specimens. A striking feature of many of the tuff breccias is the presence of angular quartz grains. In consideration of the absence of sedimentary material in the matrix of the tuff breccias, and the angular character, it appears justifiable to assume that the quartz is volcanic in source in spite of the fact that very few quartz phenocrysts are present in the associated blocks.

One interesting bed of breccia, 50 feet in thickness, was found between Oak Run and Price Hollow (Redding quadrangle). A light to dark gray porphyritic rock makes up the blocks and minor amount of matrix. Under the microscope, the phenocrysts observed were oligoclase-andesine with associated hypersthene, augite, and pale green hornblende, the latter always rimmed by magnetite. Olivine phenocrysts are rare. Quartz xenocrysts bordered by augite are conspicuous. The pilotaxitic groundmass consists of microlites of basic oligoclase and pyroxene, with magnetite as an important minor accessory.

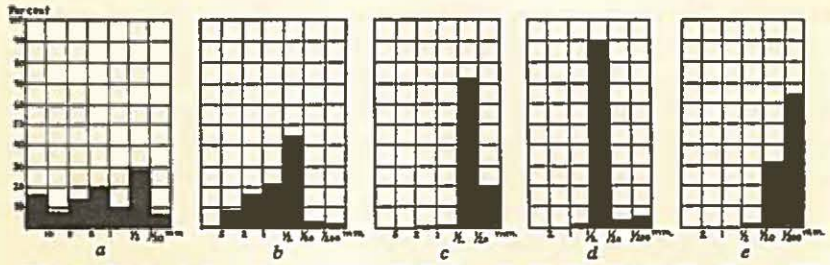


Fig. 5. Mechanical analyses of (*a*) Tuff breccia, Battle Creek (fig. 3, no. 11). (*b*) Volcanic cross-bedded sand, Big Bend of Sacramento River. Grains above 2 mm., chiefly rounded pumice. (*c*) Tuff, Big Bend of Sacramento River (fig. 3, no. 3). (*d*) Tuff, Tuscan Springs (fig. 3, no. 5). (*e*) Tuffaceous clay, Big Bend of Sacramento River.

Volcanic Sands and Tuffs

The volcanic sands and tuffs are composed of angular crystal and lithic fragments, similar to those found in the matrix of the tuff breccias. In the Redding region north of Cow Creek where dacitic and andesitic breccias are found, interbedded volcanic sands and tuffs are not common, there being only a small admixture with the underlying Tuscan-Tehama sediments. In the region to the south, the chief difference between the matrix of the tuff breccias and the finer interbedded volcanic sediments and tuffs is the well sorted character of the latter, as shown in figure 5.

The field distinction between tuffs and volcanic sands was made upon the structure. Where the beds are stratified or cross-bedded (pl. 18*a*), indicating deposition by water, they are termed volcanic sands; where massive, they are classified as tuffs (pl. 17*d*). The tuffs are all finer grained and better sorted than the volcanic sands (fig. 5).

The massive tuffs frequently contain holes and tubes which apparently contained twigs and stems of plants that have partly decomposed, but leaves are absent with the exception of rush imprints in the fine tuffs north of Red Bluff. These tubes usually have a diameter of from one-eighth to three-eighths of an inch and vary in length up to three inches.

The tuffs vary in color from bluish gray to buff to white. Usually only the very fine tuffs or tuffaceous clays are white, and this is often produced by exposure to the weather; on fresh surfaces they are commonly bluish gray. The mineralogical composition is practically the same regardless of the color of the tuff. The white tuffaceous clays (fig. 5*e*) contain minute angular fragments of plagioclase and minor amounts of ferromagnesian minerals imbedded in a matrix of clouded cryptocrystalline clay.

An interesting bed of pumice lapilli tuff ten feet in thickness is found in Iron Canyon underneath the top bed of tuff breccia (fig. 3, no. 4). Andesine crystals in the pumice indicate that the lapilli are probably andesitic. The glass is altered to brownish clay that gave good qualitative tests for MgO, SiO_2, and H_2O. The optical properties, β and γ=1.521, biaxial negative, 2V small, indicate montmorillonite (Ross, C. S., and Shannon, E. V., 1926). The clay is somewhat clouded, perhaps because of the presence of iron oxide. Other crystal-lithic tuffs frequently have a clouded yellowish brown matrix that binds the grains together, but optical data are difficult to obtain. Much of it is similar in appearance to the montmorillonite found in the pumice lapilli tuff.

Secondary white opaque opal cements the tuffs in small bands up to an inch in thickness. The secondary character is indicated by the manner in which it branches through the tuffs. A suggestion of organic structure is seen in thin section, but Mr. G. L. Whipple, of the University of California, and Professor Hubert Schenck, of Stanford University, have examined the thin sections and report that they know of no organic life to which to relate these structures. At present it must be supposed that they represent local cementation by opal. Professor Schenck has suggested to the writer that they may be a caliche deposit.

The localization of the volcanic conglomerates, volcanic sands, and tuffs in the western and southern borders of the exposures of the Tuscan formation and the petrologic similarity to the tuff breccias indicate without doubt that these deposits merely represent the reworking of the tuff breccias by streams during periods of non-deposition of the tuff breccias. The tuffaceous clays which represent the finest grained ma-

terial are only found in the extreme western and southern exposures (fig. 3). The absence of any of these clastics in the thick deposits of tuff breccias to the east implies that the tuff breccias themselves were the source. The intimate association of the tuffs with the volcanic conglomerates and volcanic sands, which were evidently deposited by water, suggests that the finer clastics were also deposited by water, in spite of the absence of cross-bedding and stratification. The well sorted character (fig. 5) is also rather suggestive of this origin.

Tuscan Buttes

The Tuscan Buttes lie just to the east of Tuscan Springs (pl. 19*a*) and rise to about 500–600 feet above the surrounding area, attaining an elevation of approximately 1300 feet. From a distance the topographic outline suggests that they are parts of a volcanic cone, and they have been referred to as such (Diller, 1894, p. 433). Upon closer examination, however, this appearance is seen to be misleading, for in reality the buttes merely represent homoclinal dipping beds of the Tuscan formation capped by a lava flow (fig. 6).

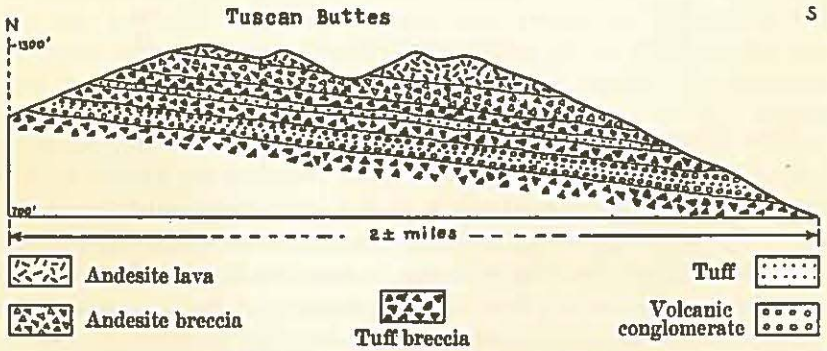


Fig. 6. Section through Tuscan Buttes.

The interest of the Tuscan Buttes lies chiefly in this lava flow and the underlying volcanic breccia which is of the same composition (fig. 3, no. 6). The breccia is composed of closely packed blocks averaging about six inches in dimension, with a minimum amount of tuffaceous matrix. The rock is pale buff in appearance with a very few scattered black hornblende phenocrysts (1.5 mm.) imbedded in a microcrystalline groundmass composed chiefly of plagioclase laths, from 0.1 to 0.2 mm. in length, principally acid labradorite in composition, with a few associated yellow-brown to greenish yellow hornblende crystals usually resorbed to magnetite dust. A few very slender hypersthene crystals are also present. The matrix between these crystals consists of abundant microlites with a very little yellowish brown glass. In contrast to the glass, a color-

less slightly birefringent mineral with a poor cleavage is present in small amount, interstitial to the plagioclase. The index of refraction is 1.488 ± .004. A sample of the rock was powdered and digested with hydrochloric acid; this solution yielded SiO_2 and Al_2O_3. There is here a suggestion that the mineral is probably analcite. If so, the rock might be classified as an analcite-bearing hornblende andesite.

The following chemical analysis is taken from Clarke and Hillebrand (1897, p. 195):

	Percentage
SiO_2	60.93
TiO_2	.61
Al_2O_3	18.56
Fe_2O_3	2.68
FeO	2.19
MnO	.10
CaO	6.63
SrO	.12
BaO	.02
MgO	2.37
K_2O	1.33
Na_2O	3.79
H_2O	.90
P_2O_5	.18
Total	100.41

Since this particular rock is only found at Tuscan Buttes and is totally different from any of the fragments found in the Tuscan formation, it appears to be of local origin. It dips conformably with the underlying Tuscan formation in contrast to neighboring basalt flows which show an angular discordance to the underlying Tuscan. This implies that the analcite-bearing hornblende andesite is of the same age as the Tuscan (Upper Pliocene) and should be included in the formation in spite of its local occurrence. It may have been related to a volcano near the present site of Tuscan Buttes, but certainly the present Tuscan Buttes are only an erosional feature and not remnants of a volcanic cone.

SOURCE

The outcrops of the Tuscan formation converge and the beds thicken to the east (figs. 1 and 3), indicating without doubt that the source of the material must lie to the east of the present exposures. On this evidence, it has been customary to refer to the source as volcanoes in the Lassen Peak region, some writers even suggesting present vents (pl. 20*b*).

Williams (1929*b*, 1931) has recently pointed out that the present peaks in the vicinity of Lassen Peak, including Lassen Peak itself, are volcanic domes, chiefly of dacitic composition. These are comparatively

recent features, certainly of much later age than the Tuscan formation. All these domes lie on the northeast flank of a great pyroxene andesite cone, of which Brokeoff Mountain is the highest surviving remnant (Williams, 1931, p. 385). This strato-volcano had a diameter of about 15 miles and a height of 11,000 feet, built almost entirely of a series of flows. Through the courtesy of Dr. Williams, the writer studied a number of thin sections from this series of lavas, and although they are chiefly hypersthene augite andesites, they do not appear to be similar to the vast majority of the fragments found in the Tuscan formation. The groundmass of the Brokeoff lavas is more feldspathic with a much smaller amount of accessory magnetite. The specimens from near the top of Brokeoff Mountain are very glassy, totally unlike any of the rocks found in the Tuscan.

On the other hand, certain pyroxene basalts which Williams* considers to be older than the Brokeoff lavas, are very similar to many fragments found in the Tuscan formation. These occur on the east side of Lassen Volcanic National Park. There the basalts frequently contain olivine and characteristically exhibit the microdiabasic texture that is so common in many of the fragments found in the Tuscan. Reference has been made (p. 229) to an andesite in the region east of Redding that contains quartz xenocrysts, and similar andesites are found in the central part of the Lassen National Volcanic Park, forming the andesites of the Central Plateau (Williams, 1931, p. 386). These are also among the older volcanic rocks. Although correlations among lavas are dangerous because of the frequent appearance of rocks of varying age yet of the same petrographic characters, if correlations of the rocks in the Tuscan are to be made with rocks in the Lassen Peak region, they must be made with the oldest volcanic rocks exposed, and certainly not with the rocks that form the present peaks.

Lavas exhibiting the microdiabasic or diabasic textures have been reported by Turner (1894, p. 493) in the region to the southeast of Lassen Peak at Mount Ingalls, and, because of their similarity to the fragments which he observed in the Tuscan in the Chico area, Turner has suggested that these lavas might be a source. Certainly this possibility cannot be positively eliminated and there is a chance that these lavas may be intimately related to the older lavas in the Lassen Peak region.

From a glance at figure 1, it is seen that the region to the east of the exposures of the Tuscan formation is covered by later andesites and basalts, and it may be that the source of the Tuscan is masked by these flows. At present, all we may say is that the source is apparently in old volcanoes that possibly existed in the vicinity of Lassen Peak; or they

* Oral communication.

may have been located still farther east beyond the confines of Lassen Volcanic National Park and are now concealed by later flows. Certainly the present volcanoes, so well developed in this region, are later in age and did not contribute to the Tuscan.

NOMLAKI TUFF

The Nomlaki tuff has been of value in correlating the various deposits in the northern part of the Sacramento Valley, for it is widespread in its distribution (fig. 1) and distinct in its appearance. It is composed chiefly of white pumice fragments imbedded in a pink, gray, or white matrix of glass and crystal shards. These crystals consist of basic oligoclase, hypersthene, and green and brown hornblende. The glass has an index of 1.505 ± .003, indicating about 70 per cent SiO_2 (George, 1924). Chemical analyses show definitely that the tuff is of dacite composition.

	1	2	3
SiO_2	65.78	67.27	69.51
Al_2O_3	14.87	14.84	15.61
Fe_2O_3	1.27	1.01	.56
FeO	1.00	.85	1.27
MgO	1.89	1.36	.61
CaO	2.41	2.30	2.80
Na_2O	2.58	2.94	3.43
K_2O	2.71	2.87	2.81
H_2O	2.87	1.55	3.63
H_2O	4.32	4.95	
P_2O_5	.08	.06	.....
TiO_2	.....	.27	Trace
BaO	.....	.15	.....
	99.78	100.42	100.23

1. Dacite tuff. Rice's Quarry, 6 miles SE of Paskenta, Tehama County. Analysis by George Steiger (Diller, 1911, p. 23).

2. Dacite tuff. 6 miles NE of Paskenta. Analysis by E. T. Allen (Diller, 1903, p. 369).

3. Dacite tuff. Stillwater Creek, 8 miles NE of Redding. Analysis by W. H. Melville (Clarke, F. W., and Hillebrand, W. F., 1897, p. 197).

The tuff may be classified as a hornblende-hypersthene dacite crystal vitric tuff.

The Nomlaki tuff has usually been referred to as the Tuscan tuff (Diller, 1894; Bryan, 1923), but Russell (Russell and VanderHoof, 1931) and the writer have proposed the name Nomlaki tuff from the good exposures on the old Nomlaki Indian Reservation in Tehama County. A separate designation seems desirable in view of its much wider distribution and value as a horizon marker and its dacitic com-

position as contrasted to the dominant andesitic and basaltic composition of the Tuscan formation.

The thickness of the Nomlaki tuff varies from 40 to 100 feet; some of this variation is probably caused by disconformable relationships to the overlying beds. Along the eastern side of the Sacramento Valley at Tuscan Springs and Antelope Creek, the Nomlaki Tuff is interbedded with the lower part of the Tuscan formation (fig. 3), while on the western side the tuff is interbedded with the lower part of the Tehama formation (Russell and VanderHoof, 1931), suggesting that these two formations are in part contemporaneous. According to Russell (1931), the source of the Nomlaki tuff is an area of dacite exposed along Digger Creek (fig. 1). The petrographic similarity and appearance of tuff in the immediate vicinity suggest this possibility.

Tehama Formation

The Tehama formation (Russell, 1931) consists of about 2000 feet of fine silty sands, sandy silts, and clays with interstratified beds and lenses of medium to fine-grained gravel. With the exception of the clays which may be partly tuffaceous, the sediments in the Tehama formation are of non-volcanic source, derived from the Coast Range and Klamath Mountains (fig. 2). Russell (1931) has suggested that the formation is essentially a fluviatile deposit laid down under flood-plain conditions in a broad and long valley, evidently a former extension to the west and north of the Sacramento Valley flood-plain.

In view of the contemporaneity of the Tuscan and Tehama formations, it is not surprising to find them interfingering. Evidence of this may be seen north of Red Bluff (Russell, 1931) and in the low hills that lie just to the east of Corning, indicating that the central axis of the old valley lay a short distance to the west of the present Sacramento River.

In the region east of Redding, the sediments above the Nomlaki tuff (fig. 4) are essentially non-volcanic, with varying admixtures of volcanic detritus. They are therefore referred to as Tuscan-Tehama sediments. As seen in figure 4, some Tuscan breccia is interbedded with these sediments, but most of the Tuscan formation in this region consists of only a veneer of tuff breccias upon the underlying Tuscan-Tehama sediments.

Age of the Tuscan Formation

Although the age of the Tuscan formation has been frequently cited as Pliocene, no paleontological evidence supporting this had been found until the recent discovery in the Tehama formation of vertebrate fossils by Mr. S. D. Furber, of Red Bluff (Russell and VanderHoof, 1931, p. 17). Additions to the fauna were recently discovered and described

by VanderHoof (1933). The following faunal list represents the fossils that have been found to date:

Reptilia
  Testudo sp.
Carnivora
  Hyaenognathus cf. *pachyodon* Merriam
  Canis sp.
Ungulata
  Plesippus cf. *proversus* (Merriam)
  Camelops or *Pliauchenia*
  ? *Antilocapra* sp.
  Odocoileus sp.
  Prosthenops or *Platygonus*
Proboscidea
  Stegomastodon cf. *Arizonae* Gidley
Edentata
Megalonychid gen. and sp. indet.

According to VanderHoof (1933), this assemblage suggests that the beds containing the fossils represent a faunal stage just later than Upper Etchegoin (*Plesippus proversus*) stage. A number of forms appear to be the forerunners of groups which reach their maximum development in the Lower Pleistocene, so VanderHoof has concluded that the Tehama formation may be regarded as containing a true Upper Pliocene fauna.

These fossils, consisting of scattered teeth and foot bones, are found 18 miles west-northwest of Corning in Tehama clays. At one locality, bone fragments were found 10 feet above the Nomlaki tuff, and since there is no stratigraphic break between the fossil beds and the tuff, the fossils determine the age of the tuff. Fossils were collected several miles to the east in two horizons, 200 feet apart stratigraphically, the species apparently being identical, the lower horizon occupying the same position stratigraphically as in the first locality.

With the finding of these fossils, the Nomlaki tuff becomes a very important horizon marker, especially in its relationship to the Tuscan formation. As previously mentioned, the Nomlaki tuff with a maximum thickness of 100 feet is exposed at Tuscan Springs, interbedded with the Tuscan formation near the base, 40 feet of Tuscan breccias, sands, and conglomerates lying between the Nomlaki and Cretaceous at this point. Farther to the south at Antelope Creek, 40 feet of Nomlaki tuff are interbedded between tuff breccias of the Tuscan formation. This clearly indicates that the Tuscan formation is Upper Pliocene in age.

STRATIGRAPHIC POSITION OF THE TUSCAN FORMATION

By referring to figure 3, it is seen that in some sections the Tuscan formation rests directly upon Upper Cretaceous sandstones and shales of the Shasta-Chico series; in others, the formation is separated from

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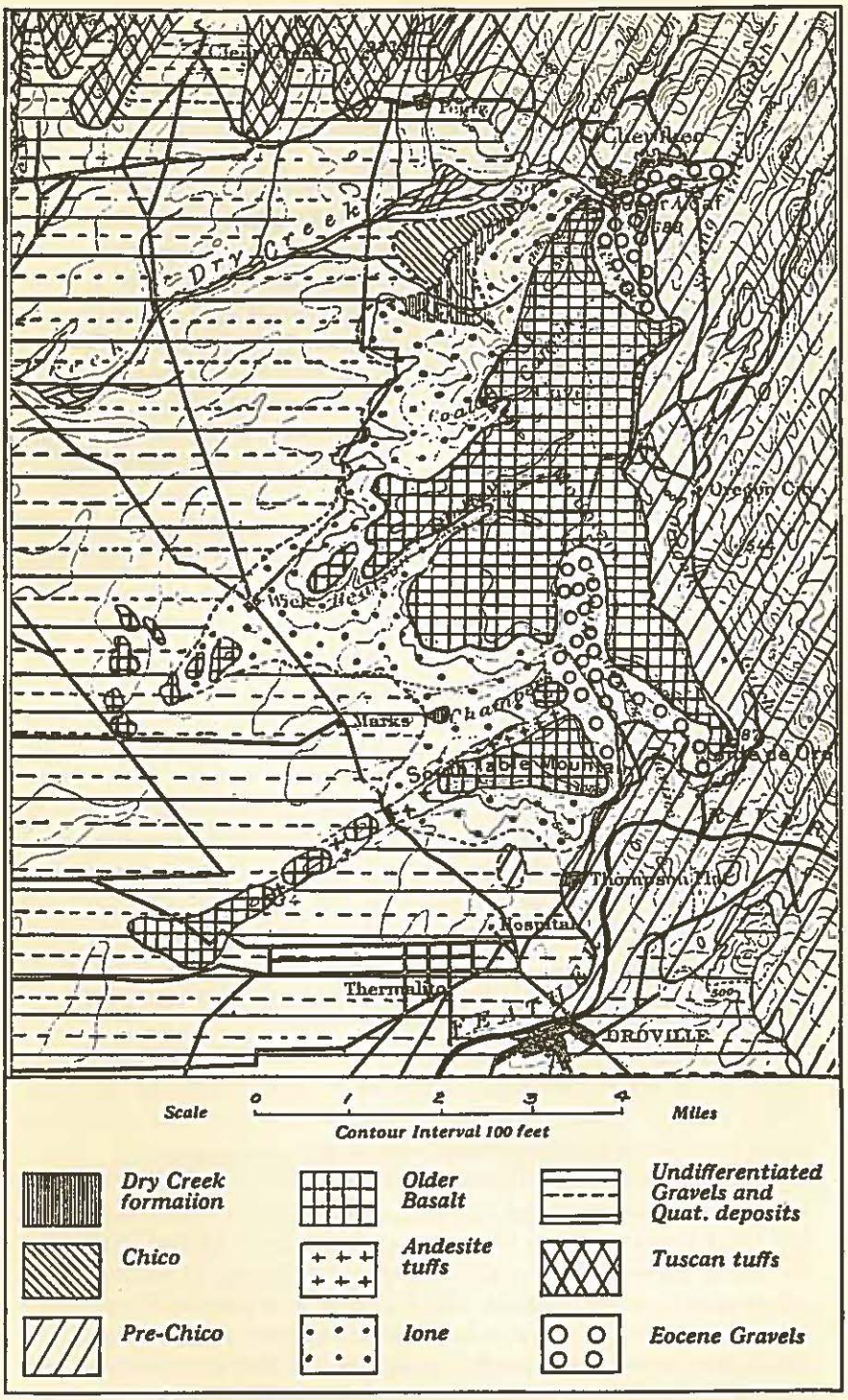


Fig. 7. Geological map of part of the Chico quadrangle, California.
From Allen (1929, p. 367).

the Cretaceous by non-volcanic gravels of probable Tertiary age. In the Redding area, the Tuscan-Tehama sediments usually rest upon Chico sandstones and shales.

The basalt flow in Chico Creek at the base of the Tuscan formation is very similar in appearance to the basalt flow that caps Oroville Table Mountain to the south. But at the latter locality, the relationship of the Tuscan formation to the basalt is somewhat different. As may be seen by reference to figure 7, the Table Mountain basalt (the "older basalt" of Turner, 1896, p. 543) rests chiefly upon the Ione formation (Middle Eocene), but at South Table Mountain a thin bed of andesitic tuff underlies the basalt (Allen, 1929, pp. 366–375). Turner (1894, pp. 494–495) has traced this basalt to the east where it is overlain by andesitic breccias at Mount Ingalls. It may be, therefore, that the basalt is interbedded in the Sierran andesitic series.

At Welch's Hydraulic Mine, about one mile north of Pentz, 75 feet of sands and gravels at the base of the Tuscan formation rest upon Paleozoic slates (fig. 3, no. 10), and these gravels contain abundant subangular fragments of the Table Mountain basalt. Since the Tuscan formation extends almost to the level of the Sacramento Valley with the base from 500 to 1000 feet lower than the basalt of Table Mountain, and since the Ione and Chico formations are absent, considerable erosion is indicated between the outpouring of Table Mountain basalt and the deposition of the Tuscan formation. Moreover, since the Table Mountain basalt appears to be interbedded with the Sierran andesitic breccias, the suggestion is very strong that the Tuscan formation is younger than the Sierran andesitic series. Louderback (1924, p. 19), in considering the age of the Sierran andesitic series, has concluded that they are "Lower Pliocene or Upper Miocene, perhaps bridging the gap between these two epochs." Since the Tuscan formation is Upper Pliocene, it seems well established that the Tuscan formation is younger than the more or less similar andesitic series to the south.

In speaking of the Pliocene age of the Tuscan formation, Bryan (1923, p. 72) states that small eruptions of similar material have continued through Quaternary time to the present day. The writer has found no evidence that supports this view.

Red Bluff formation.—In the area from Bellavista to Red Bluff, the Tuscan formation is capped by red gravels, called by Diller (1906) the Red Bluff formation from its typical exposure north of Red Bluff. This formation appears to be an alluvial deposit composed of subangular to sub-rounded pebbles, cobbles, and boulders in a matrix of red sandy clay. The coarser material is found near Redding and the deposit becomes finer toward Red Bluff. The age of the Red Bluff formation is usually assigned to the Pleistocene although no paleontological evidence is at hand to substantiate this. The basis of the age determination ap-

pears to be the distinctive red color of the matrix as contrasted to the dominant grays of the Recent alluvial deposits and the fact that the Red Bluff formation is unconformable above the Tehama and Tuscan formations. Since the present streams have frequently cut their canyons as deep as 300 feet (Iron Canyon) below the Red Bluff, it does not seem desirable to place the Red Bluff in the Recent.

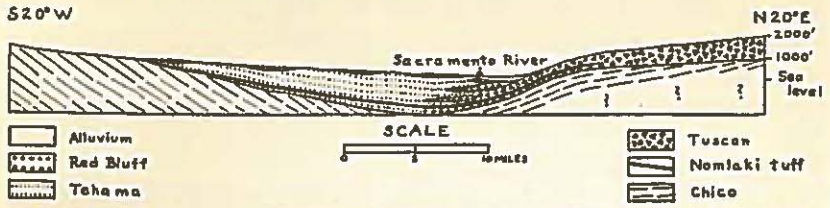


Fig. 8. Idealized cross-section through the Sacramento Valley south of Red Bluff.

West of Red Bluff and in the Millville region the Tehama and Red Bluff formations are usually nearly flat lying and are separated by disconformities. But along the west side of the Sacramento Valley, as pointed out by Russell (Russell and VanderHoof, 1931, p. 13), the Tehama beds dip to the east at angles between 3° and 6° and are definitely truncated by the Red Bluff formation (fig. 8). Between Iron Canyon and Tuscan Springs, the writer found Red Bluff gravels truncating tuffs and tuff breccias of the Tuscan formation with an angular discordance of 10°.

Basalt flows.—The sequence of events in this general region is complicated by the extrusion of basalt flows varying in age from post-Tuscan pre-Red Bluff to Recent (?). Many of these occur only as isolated erosional remnants resting upon the Tuscan formation, but none have been found by the writer to be interbedded. At Tuscan Springs, the Tuscan formation was folded and a canyon cut down to the Nomlaki tuff before the extrusion of a basalt flow (fig. 9). This particular basalt flow is now represented by a small erosional remnant far above the present canyon.

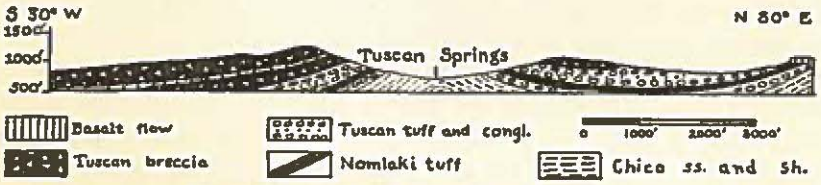


Fig. 9. Cross-section through Tuscan Springs.

A similar feature is shown at Table Mountain (another Table Mountain, bordering the Sacramento River north of Red Bluff) where a basalt flow truncates the underlying members of the Tuscan formation (fig. 10). This particular basalt flow is capped by Red Bluff gravels (fig. 11),

which proves that it is post-Tuscan-pre-Red Bluff in age. Another basalt flow, however, followed the present course of Paynes Creek to the Sacramento River (fig. 12), possibly filling Iron Canyon for a short distance. Since then, all traces have been removed from Iron Canyon; Paynes Creek was displaced by the lava, and it has since cut a new canyon through the basalt and into the underlying Tuscan formation for a depth of 50 feet (Hamlin, 1920, p. 50). This flow is obviously much later in age than the Red Bluff formation and evidently younger than many of the other basalt flows that are present in the region. It may be very late Pleistocene to Recent.

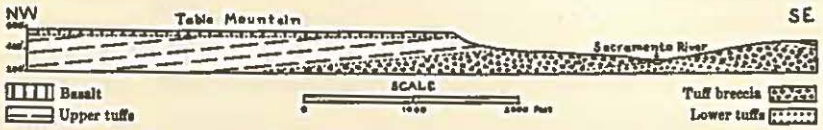


Fig. 10. Cross-section at Table Mountain, northeast of Red Bluff.

The source of these various basalt flows is difficult to determine, since many occur only as isolated erosional remnants, but the wide distribution of basalt to the east, covering many square miles, indicates an eastern source. The Paynes Creek basalt appears, however, to be related to the lava cone that makes up Inskip Hill (pl. 20*b*) and probably has flowed only a comparatively short distance.

It is evident that the basalt flows have no value in correlation, for they may vary in age from pre-Tuscan (along Chico Creek and Oroville Table Mountain) to post-Red Bluff (Paynes Creek basalt at Iron Canyon).

STRUCTURE

In the area east of Redding, the Tuscan-Tehama sediments dip uniformly at low angles toward the southwest (fig. 4). From the southern margin of the Tuscan formation to Chico, homoclinal dips of 2°–3° characterize the Tuscan as it gradually passes under the alluvium of the valley. North from Chico to Red Bluff, the western border of the Tuscan is marked by a sharp monoclinal fold (fig. 8) which accounts for the rather straight line along the southwestern border of the exposed area of the Tuscan. The dips of the beds in the monocline increase to the northwest; at Mill Creek the dip is 8°–10° SW, while at Antelope Creek it is 20° SW. The beds to the east of the flexure have a westerly dip of 2°–3° (fig. 13). The appearance of the Nomlaki tuff on the west side of the Sacramento Valley and again in the core of a well near Orland (Russell, 1931) indicates the flattening of the beds under the valley (fig. 8).

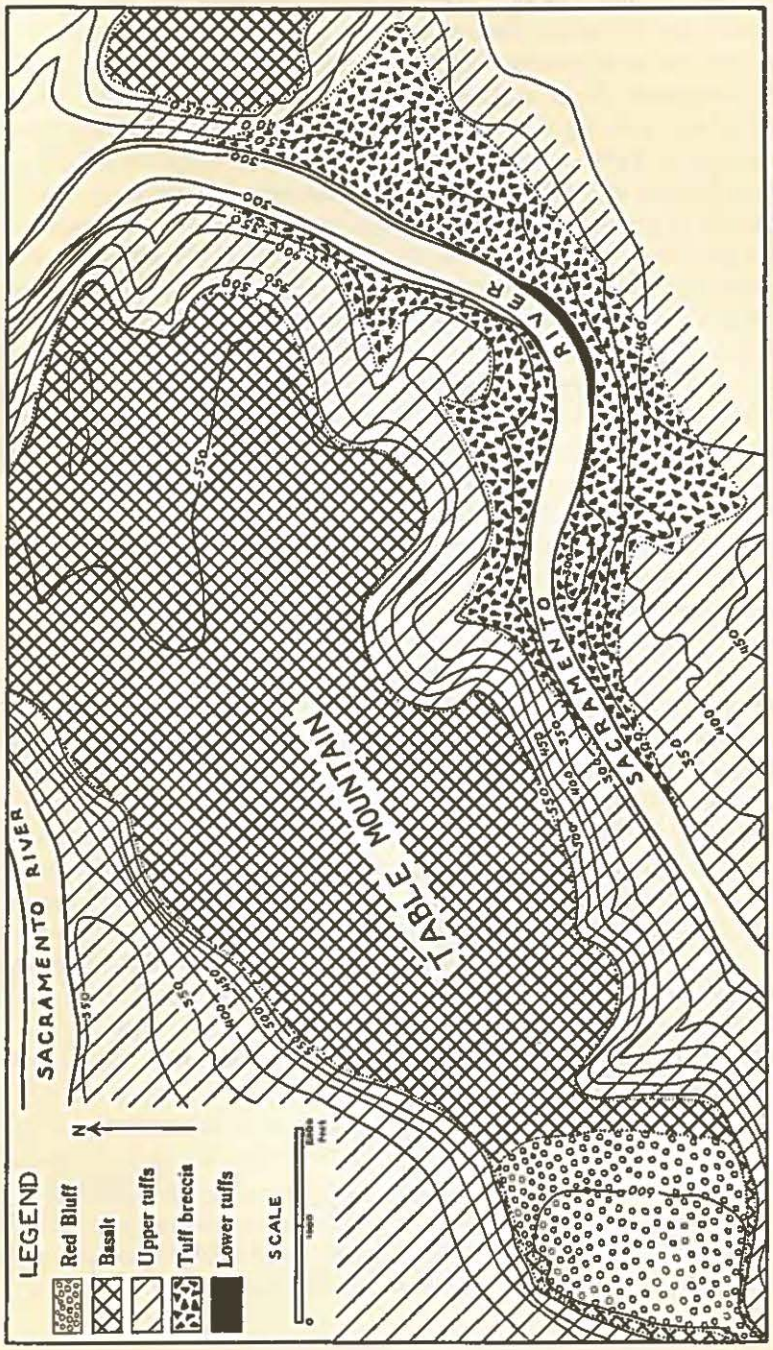


Fig. 11. Geologic map of Table Mountain, northeast of Red Bluff. Modified from Marliave (1930).

The monoclinal structure is lost in the neighborhood of Red Bluff, for the beds are folded at Tuscan Springs (fig. 9) into an anticline and syncline. An arch trending more or less northwest-southeast cuts across the Sacramento River at Iron Canyon (Diller, 1894, p. 433; Hamlin, 1920, p. 46). (See fig. 12.) Another anticline is developed in the Tuscan formation at Table Mountain north of Red Bluff (figs. 10 and 11). At the confluence of Battle Creek and the Sacramento River, a synclinal structure is present, masked somewhat by the presence of massive volcanic gravels. However, about a mile south of Battle Creek, a bed of tuff breccia dips 15° northwest under the massive gravels. Near the base of these gravels, a few intercalated beds of tuffs and volcanic sands have the same dip, showing that the gravels are conformable with the tuff breccias. The north bank of Battle Creek is capped by basalt flows which are underlain by the same massive gravels. Halfway down the north slope to Battle Creek, an intercalated 10-foot bed of tuff dips 10° southwest, indicating the synclinal structure. In all probability other folds may be discovered in the future in this general region.

Judging from the angular discordance between the Red Bluff formation and the underlying Tuscan formation, much of this folding took place prior to the deposition of the Red Bluff gravels. There must have been some uplift, however, since the deposition of the Red Bluff, to account for the present incision of many of the streams, particularly the Sacramento River as it cuts through Iron Canyon and at Table Mountain. Russell (1931) has suggested that the Red Bluff also has been deformed, deformation probably following the axes of earlier folding.

At Table Mountain, however, where the Tuscan formation has been anticlinally folded, the evidence is quite clear that the Red Bluff formation was not involved in the folding. The Table Mountain basalt has not been deformed along the anticlinal axis (fig. 10), and Red Bluff gravels cap the southern end of Table Mountain. The entire surface of the basalt flow is covered by a mantle of Red Bluff pebbles and cobbles, indicating that the entire surface was covered at one time by the Red Bluff. The basalt appears to have a slight dip to the northeast, which may be the result of the general regional uplift that brought about the intrenchment of the Sacramento River.

The Red Bluff gravels at Table Mountain are at about the same elevation as the gravels that are present at Iron Canyon (figs. 11 and 12) and similar elevations to the west are also covered by Red Bluff gravels. At present no positive evidence is available suggesting that the Red Bluff gravels are involved in the folding in the neighborhood of Red Bluff; indeed, the evidence points to the contrary.

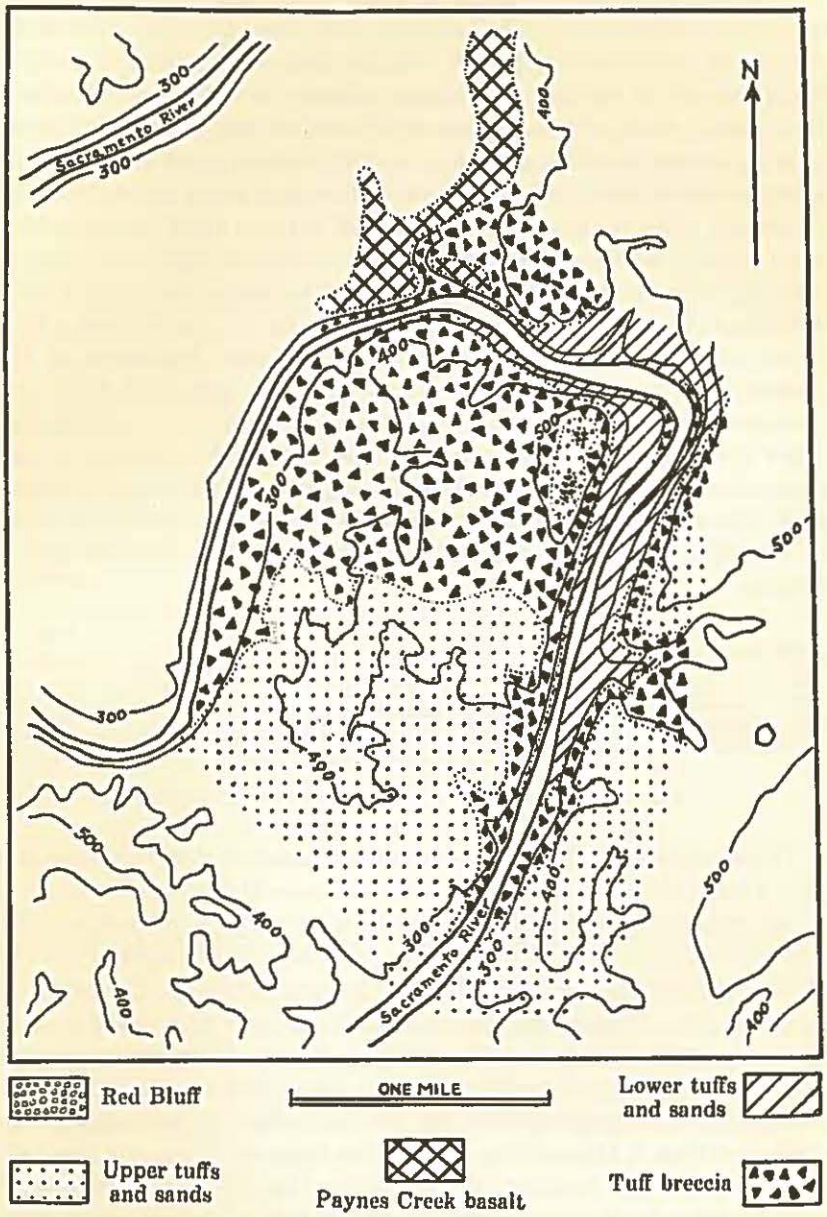


Fig. 12. Geologic map of Iron Canyon, northeast of Red Bluff. From Hamlin (1920).

Diller (1894, p. 433) has suggested that the Sacramento River is antecedent where it cuts through the arch at Iron Canyon, implying that the Red Bluff formation was folded. But the large areal extent of the Red Bluff gravels at uniform elevations indicates a wide, well developed flood-plain; more or less vertical uplift incised the Sacramento River into its present position so that it is superimposed upon the anticlines of Iron Canyon and Table Mountain, rather than being antecedent.

Twenty miles to the south of Red Bluff, the Red Bluff formation has been slightly deformed. On the west side of the low hills to the east of Corning (Vina quadrangle), the Red Bluff formation has a small westerly dip in contrast to regional easterly dip (fig. 8). On the east side of these hills, the easterly dip has been accentuated. Exposures of the underlying Tuscan-Tehama sediments show an anticlinal fold with stronger dips indicating an angular discordance with the overlying Red Bluff formation and suggesting that the Red Bluff formation at this particular locality has been deformed along the axes of earlier deformation. This may be the locality that Bryan (1923, p. 79) referred to when he stated that the older alluvium (Red Bluff) was involved in the folding.

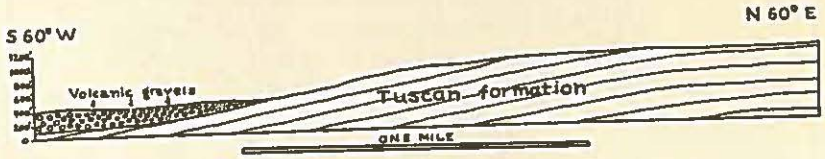


Fig. 13. Cross-section along Mill Creek, east of Tehama.

If one studies the Tehama and Vina quadrangles, it is very apparent that a large alluvial fan has been built up opposite Mill Creek and Deer Creek, yet, curiously, the fan is not being built up by the present streams, but is being destroyed. Deep gorges are present in the apex of the fan while the distal end is being dissected by small streams. The rocks exposed in these stream canyons are volcanic gravels and volcanic sands and some might even be classified as tuffs. At first glance, they appear to belong to the Tuscan formation, for they are similar to interbedded volcanic sands and conglomerates. As one approaches the monocline at the apex, however, it is seen very clearly that these sediments truncate the folded Tuscan and butt into the monocline (fig. 13). Since the present Mill Creek is flowing in a gorge about 150 feet below the top of these gravels, it appears that they may be equivalent to the Red Bluff formation.

A well developed terrace that truncates the folded Tuscan and is developed in the volcanic gravels described above, is incised by a very narrow gorge containing Mill Creek (pl. 18*d*). Diller (1889, p. 426) has

described the same feature and concluded that it indicated a post-Pleistocene uplift. It would correspond to the post-Red Bluff uplift if these volcanic gravels opposite Mill Creek are of Red Bluff age, but the amount of uplift would be much smaller than in the region above Red Bluff, so the post-Red Bluff uplift may have been in the nature of a broad arch. Perhaps when adequate maps are available for the plotting of the Red Bluff gravels and possibly later terrace gravels, the answer will be known.

The post-Tuscan history may be summarized as follows:

1. Production of local folds in the Tuscan formation followed by erosion that removed the upper beds in some localities and even cut canyons down to the Nomlaki tuff (Tuscan Springs).
2. Extrusion of basalt flows that overlie the Tuscan, with angular discordance in some places.
3. Deposition of the Red Bluff gravels.
4. More or less vertical uplift, possibly in the nature of a broad arch, resulting in the erosion of the present deep canyons. (Superposition of the Sacramento River upon the folds in the Tuscan formation.) Local folding of the Red Bluff (east of Corning).
5. Extrusion of more basalt (Paynes Creek basalt).

Russell (Russell and VanderHoof, 1931, p. 16) has summarized a similar history for the southeast quarter of the Redding quadrangle:

1. Erosion of valleys through more than 100 feet of the Tuscan and Tehama formations and into the Chico formation.
2. Extrusion of basalt flows which came down these valleys.
3. Deposition of the Red Bluff formation.
4. Erosion of the present canyons, which are not related to the earlier ones.

MODE OF EMPLACEMENT OF THE VOLCANIC BRECCIAS

In most of the early papers, discussion as to the mode of origin of the volcanic breccias of the Tuscan formation was usually omitted, except to remark that the material was probably derived from volcanoes in the Lassen Peak district. Diller (1889, p. 423) once suggested that part of the material was ejected during violent volcanic eruptions and carried by the wind, while Lindgren (1911, p. 88) thought that the deposits were left by mud streams.

Lacroix once stated that the origin of volcanic breccias and volcanic conglomerates (Lacroix uses the term volcanic conglomerate for a volcanic breccia that has been emplaced by water) is more complex than one would think at first and may be susceptible to many interpretations. He outlined the various ways in which breccias have formed in the Antilles and Vesuvius (Lacroix, 1906, p. 635), and the writer has adopted

his outline with modifications and additions. Volcanic breccias may have the following origins:

I. Volcanic breccias not transported by water
  A. Crumbling of a dome (*brèches d'écroulement*)
  B. Intrusion (massive *pépérites*)
  C. Friction
  D. Crumbling of advancing lava flow (blocky lava)
  E. Eruptions
    a. Vulcanian
    b. Peléan (*nuées ardentes*)
    c. Ultra-vulcanian (Bandai-san)
  F. Dry avalanche (Vesuvius)

II. Volcanic breccias transported by water (the conglomerates of Lacroix [1906], Wolff [1913, p. 405] and others)
  A. Eruptions
    a. Through a crater lake
    b. Melting of snow and ice
    c. Following heavy rains
    d. Accompanied by heavy rains
  B. Not related to eruptions
    a. Collapse of the dam of a crater lake
    b. Heavy rains falling on unconsolidated ejecta
    c. Rapid melting of snow and ice (Mount Shasta)

VOLCANIC BRECCIAS NOT TRANSPORTED BY WATER

The protrusion of domes and spines as at Mont Pelée and Lassen Peak (Lacroix, 1906, p. 636; Williams, 1929*b*, p. 317) is usually followed by a collapse of the dome and production of a mantle of talus, which may develop local deposits of breccia (*brèches d'écroulement*). Obviously such a local breccia is not the type found in the Tuscan formation. There is no evidence pointing to the intrusion of magma into wet sediments producing *pépérites*. Friction breccias are supposedly developed by differential movements of solid lava, as in the spine on the summit of Mont Pelée, and this possibility may be readily dismissed. The abundance of matrix in the Tuscan breccias eliminates any comparison to blocky laval flows. As Wentworth and Williams (1932) suggest, probably very few geologists would be willing to classify the above breccias as pyroclastic.

Vulcanian eruptions.—Vulcanian explosions usually break up preexisting solid rock into angular débris and fine dust, and the cloud rises slowly above the crater, the material subsequently falling about the slope of the volcano or back into the crater. The blocks are arranged according to size, the coarser material falling near the crater, while the distribution of the finer material is influenced by the wind. Vulcanian explosions are usually separated by frequent intervals, so that the deposits are more or less stratified and sorted. In the breccias of the

Tuscan formation, no lateral gradation in size of fragments is apparent. Indeed, some of the largest fragments observed were near the western (pl. 19*b*) and southern margins of the exposed breccias, while the thickening of the deposits toward the east indicates the source to be in that direction. The lack of sorting, both laterally and vertically, casts extreme doubt upon vulcanian explosions as a decided factor in the emplacement of the Tuscan volcanic breccias.

Peléan eruptions.—Within the last three decades, Peléan eruptions (*nuées ardentes, Glutwolken,* glowing clouds) have been given important consideration as a factor in the production of coarse and fine pyroclastic rocks. In the classic work of Lacroix (1904) on the eruption of Mont Pelée, a number of beautiful photographs are shown of breccias containing fragments several yards in diameter, deposited by *nuées ardentes,* and the similarity to the volcanic breccia deposits of the Tuscan formation is very striking.

According to Lacroix (1906, p. 642), the Peléan eruptions present a type of vulcanian explosions except that the deposits are thicker and more compact. The cloud moves rapidly from the heights to the plains. It is of large mass, has a high temperature and a great velocity. The launching of the cloud, semi-gaseous and semi-solid, is determined by the combined action of initial explosions and gravity. The progress down the slope is facilitated by the extraordinary mobility which fine powder possesses at high temperature, and this mobility may be augmented by the expanding gas and water vapor. The material carried by the Peléan *nuées ardentes* includes enormous blocks and fine powder, and produces an avalanche of a special nature. The structure of the deposits is essentially chaotic, ranging from large blocks to impalpable dust, but topographical obstacles have in some places checked the passage of large blocks so that deposits at the distal ends contain fragments limited to 4 and 5 centimeters in diameter. At Mont Pelée, blocks several tens of cubic meters in size were carried 6 kilometers from the crater together with fine cinders, while, in vertical projection, blocks much smaller were not carried over 2 kilometers from the crater.

In a later paper, Lacroix (1908, p. 78) distinguishes two types of Peléan eruptions. In one the explosion is vertical, but instead of rising into the atmosphere, as is the action of vulcanian clouds, the mixture of solid material and gas, owing to its weight, falls as a mass upon the flanks of the mountain and rolls as an avalanche with an accelerated velocity. In the second type, the explosion is oblique and the cloud assumes a direction determined by the position of the opening. The force of the projection added to the weight aids in the movement of the cloud down the slope. The cloud changes its volume rapidly by dilation of the volatile constituents so that the cloud *en marche* is animated by two movements, a horizontal translation and a vertical dilation.

Anderson and Flett (1903, pp. 509–510) believe, however, that the weight of the mass is the source of the energy driving the cloud along.

> The motive power is supplied by the weight of the mass. It is in a condition comparable to that of a heavy and mobile fluid which has been elevated by the volcanic forces and poised on the edge of the crater and proceeds to flow downward in obedience to the law of gravitation..... Gravity did the work and supplied the energy. There was no explosion..... But these discharges are not merely avalanches; they are more, for they have properties unlike those of avalanches, and by means of which they approach more closely to blasts. In an ordinary avalanche the gases are more or less accidentally involved, and form only a small part of the whole mass. But here their presence is essential; they are an original part of the mass, and without them there would be no flow. They are expanding, surging of their own inherent energy, and lift the dust and sweep it along, while the dust in turn fetters them and compels them to keep to the surface of the ground.

Fenner (1923, p. 71) would add a third factor to the development of a *nuée ardente*.

> This is the self-explosive property inherent in the magma itself, due to the presence and evolution of dissolved gases; this explosive evolution is not manifested immediately, but is prolonged over a considerable portion of time during which the spreading movement continues, and gives to the material its fundamental characteristics of quasi-liquidity. Gravity plays an important part in directing the flow down mountain slopes or along topographic depressions, but it is believed that its effectiveness would be rather insignificant were it not for the peculiar properties imparted by the form of disintegration described.

In considering Peléan eruptions as a possibility for the development of the breccias in the Tuscan formation, it must be borne in mind that such eruptions would have to take place on a much grander scale than heretofore observed in any recent volcanic eruptions. The *nuées ardentes* at Mont Pelée and Soufrière rushed down slopes of 12°–15°, and even on such slopes part of the material was deposited in the upper portions of the course. The *nuées ardentes* on these two islands were limited in their advance by the ocean, which readily cooled them and checked their progress. The *nuées ardentes* from Mont Pelée of December 16, 1902, and January 25, 1903, deposited fine cinders to a thickness of 50 centimeters at the mouth of Rivière Blanche, 6 kilometers from the crater, and this was down a slope of 12°–15° (Lacroix, 1904, p. 210). When the slope angle of 2°–3° of the Tuscan breccia and the linear exposure of at least 30 miles, are compared with the Mont Pelée example, one must doubt the power of *nuées ardentes* to deposit the breccias of the Tuscan formation.

On the island of St. Vincent, the deposits left by the passage of *nuées ardentes* are of much greater magnitude than those on Martinique (Anderson and Flett, 1903, p. 489), but here the distance traversed ranges from three to four miles. A striking feature of the deposits on St. Vincent Island is the scarcity of coarse material, for, according to Anderson

and Flett (1903, p. 432), "Certainly over 90 per cent of the whole could only be described as volcanic sand, and often the fragments above a couple of inches in diameter did not form over 3 per cent of the mass." There is, of course, no comparable feature characterizing the deposits in the Tuscan formation.

The interpretation placed by Fenner (1923) upon the tuff deposits of the Valley of Ten Thousand Smokes is of interest, for he has suggested that these deposits also accumulated as the result of Peléan eruptions. Here the tuff deposits have a thickness of several hundred feet in places and consist of fine-grained "ash" containing pumice fragments from minute size up to four inches or more in diameter. Fenner has estimated that there is a little more than a cubic mile of material in the Valley of Ten Thousand Smokes, a much greater amount than that erupted at Martinique and St. Vincent. But of course there is no similarity in the general structure of the tuff deposits of the Valley of Ten Thousand Smokes and those of the Tuscan, for pumice fragments and fine ash are not the common features among the latter.

Another feature should be touched upon in considering Peléan eruptions as a possibility. Lacroix (1908, p. 206) stated that fragments of old rocks are never carried along with the *nuées ardentes,* but that they are not rare in vulcanian explosions. Anderson and Flett (1903, p. 507) imply the same condition in the following statement:

> In considering this property of perfect fluidity, which the black cloud possesses, we must remember its origin. Within the crater, it was a molten magma, in which a considerable number of small crystals floated in a liquid which contained enormous quantities of occluded steam. As it rose in the throat of the volcano, the relief of pressure allowed the gases to expand, and to free themselves from the liquid in which they were held. Sooner or later the cohesion of the liquid was overcome, and from a spongy froth the mass changed to a cloud of particles, mostly solid, but, perhaps in some part liquid, each surrounded on all sides by films of expanding gases, and thus the mixture of the ingredients from the first was perfect. Around each grain of dust there was a film of gases ready to expand enormously when the mass reached the upper air.

In the Valley of Ten Thousand Smokes, most of the erupted material was new material, and, according to Fenner's (1923, p. 35) explanation for the movement of *nuées ardentes,* contemporaneous material must be present in large amount to supply the gas which is necessary to form the emulsion, as it is termed by Lacroix. Now in the Tuscan breccias, fragments of old rocks are abundant. An avalanche composed largely of old rocks would not have the motive force to move down slopes of low angle of repose. In the Valley of Ten Thousand Smokes the final angle of repose was only 1° 08′. Fenner (1923, p. 62) supposed that the tuff was able to move over such a low slope owing to the rapid escape of the gases previously dissolved in the magma. That the magma was actually rich in

dissolved gases is evidenced by the glass pumice fragments. Since little fresh magma was erupted with the Tuscan rocks, the expansion of dissolved gases can hardly be invoked as a motive power.

Another factor to be considered is the loss of these gases through dilation and escape as the mass rushes down the slopes. Over distances of from 3 to 4 miles this escape might not be so great; in fact, the occurrences in the Antilles and Alaska indicate it is not. The case of the Tuscan deposits is, however, very different, for here the breccias were transported distances of from 30 to 40 miles and probably farther. Even during the short passages on Mont Pelée, this vertical dilation was important enough to carry up much of the fine dust that gradually settled later (Lacroix, 1904, p. 210). Over the great distances traversed by the deposits of the Tuscan formation, this dilation and escape would be considerable, and it is inconceivable that the dry material would sweep downward over a slope of 2°–3°. Cooling by the ground and air over these distances would certainly have some effect.

When we keep in mind the composite nature of these discharges, it becomes possible for us in some measure to understand the peculiar properties they possess at different points in their course and in different stages of their development. When they rise from the crater the gases are in a condition of indescribable turmoil, and buoy up the vast quantity of hot sand they bear with them. Each solid particle is cushioned on gases violently expanding, and the temperature of the whole mass is exceedingly high. Hence it seems quite probable that the black cloud rushes upwards, and may even shoot some distance into the air and fall back upon the slopes of the mountain when its first impulse is spent and its first heat has cooled. We may, at any rate, believe that the whole mass has then a mobility which it no longer possesses, when by the expansion of the gases, by mixture with the air and by contact with the ground, its temperature has been lowered, and the solid matter is beginning to segregate from the gaseous, each taking its own course.—(Anderson and Flett, 1903, p. 511.)

Breccias very similar in appearance to the Tuscan breccias occur at Marysville Buttes, California, and Williams (1929*a*, p. 183) has suggested that they are the result of Peléan eruptions. But these breccias are arranged about a central crater and they only reached a distance of from 4 to 5 miles from the source, so that their occurrence is hardly comparable to that of the Tuscan breccias.

It must be concluded from a consideration of the character of the breccias, slope angles, and great distance traveled by the breccia, that Peléan eruptions as a mode of emplacement must be dismissed.

Ultra-vulcanian eruptions.—The eruption of Bandai-san, Japan, in 1888, furnishes another type of breccia-producing activity. Sekiya and Kikuchi (1890, p. 106) have described this eruption as follows:

The most striking feature in the whole of this eruption was the deluge of rock and earth. Notwithstanding the violence of the phenomena, and the completeness with which the mountain was destroyed, the nature of the eruption was comparatively simple. The destructive agency was merely the sudden expansion of imprisoned steam, unaccompanied by lava flows or pumice ejection. When the explosion took

place, a considerable amount of rocks and earth was projected into the air, and part diffused in the form of dust, but by far the greater bulk of Kobandi was just split into mighty fragments, which were thrown down much after the manner of a land slip. Descending the mountain sides with ever accelerating velocity, the components of these avalanches were dashed against obstacles in their way and against each other, and were thus rapidly reduced to confused masses of earth and rocks. The loose and friable *débris* thus produced ultimately lost its adhesive power, and may have been compared with little exaggeration to sand. If we suppose a mass of some 1.21 cubic kilometers, or 1,587 millions of cubic yards (which was the actual volume of the mountain destroyed) of sand to be suddenly precipitated from a lofty summit, it would flow down the sides in a torrent not very unlike that of water.

This débris devastated an area of 27 square miles in the valley below, and part of the avalanche even ran up the valley of the River Nagase, stopping about 9 kilometers from the source. In the valley below, it was estimated that the débris reached a thickness of 40 meters.

This type of eruption, characterized by steam explosions and the absence of new ejecta, has been defined as *ultra-vulcanian* by Mercalli (1907, p. 148) and as *semi-volcanic* by Lacroix (1908, p. 83; 1930, p. 46). Although an explosion initiates this type of avalanche, gravity is the controlling factor in supplying the energy, and it is very doubtful whether a dry avalanche would sweep down gentle slopes covering the distance necessary for the deposition of the breccias of the Tuscan formation.

Williams (1928, pp. 241–263) has recently suggested this type of eruption and avalanche for a deposit of breccia north of Lassen Peak, but here the area covered is small, about two square miles, and not comparable with that of the Tuscan breccias. In the Lassen occurrence, the breccia came to rest in the valley below after traveling a distance of about three miles.

In the eruption of Semerou, Java, in 1885, a dry avalanche was developed somewhat differently from that at Bandai-san. According to Verbeek and Fennema's (1896, pp. 718–720) description, lava rose to the edge of the crater without any particularly violent explosion, but the hydrostatic pressure was so great that a portion of the walls gave way, producing an avalanche that rushed down the slopes to the plains below, covering an area of 6 square kilometers with débris to a thickness of 4 meters. Verbeek and Fennema (1896, pp. 714–719) also explained the catastrophe of Papandaian, August 11–12, 1772, by the same process, for, following a violent eruption which did not last 5 minutes, a rock avalanche was produced covering an area of 20 square kilometers to a thickness of 3 meters. Unfortunately no lengths are given of distances traveled by these avalanches, so that comparison with the Tuscan breccias is difficult. But these avalanches appear to be dry avalanches with gravity as the moving force, and as such would not be expected to travel far after reaching the plains below the volcanoes.

Dry avalanches are not necessarily related to explosive activity, as, for example, those which occurred on Vesuvius, so admirably described by Perret (1924, p. 90):

> The accumulation of ejected material upon the upper portions of the cone attained a depth which at times and in places was not less than 15 meters. This material consisted partly of blocks and cone detritus, but principally of deep, superposed strata of fine ash, intensely hot. This material was not only poised in exceedingly unstable equilibrium, but was in a peculiar state of potential mobility, due to the high temperature and consequently *dilated* condition of the interstitial gas. Under these circumstances there was needed only a strong tremor from below or the fall of a heavy boulder from above to detach tons of this material which (in virtue of the peculiar conditions described above) descended the flank of the mountain with the velocity and aspect of a snow avalanche in the Alps..... These hot-ash flows continued at intervals for many days, and their contribution to important morphological alterations through transportation of material, with the formation of breccias and the furrowing of the cone with channels as guides for subsequent erosion was a distinct feature of the great eruption.
>
> The *nuée ardente* differs fundamentally from the simple hot avalanche in that it is caused by the upward and outward projection of material that is immediately derived from and still retains some of the characters of the active, gas emitting magma, especially its very high temperature. The *nuée ardente* is thus directly connected with, or forms part of, the explosive activity.

That the transportation of the material is caused by gravity alone is shown by the lagging back of the dust clouds from the advancing mass. The accumulation of this material at the base of the cone has developed many imposing masses of breccia. Although the mobility of these avalanches was probably increased by the high temperature of the gas between the particles of ash, and the high slope angles of the cone, the material came to rest at the base of the cone (Perret, 1924, pl. 11) and was not spread out in a fashion comparable to that of the Tuscan breccias.

VOLCANIC BRECCIAS TRANSPORTED BY WATER

We may now consider volcanic breccias produced by the aid of water, usually from the so-called mud flows that accompany and follow many volcanic eruptions. Frequently these mud flows are intimately related to the phenomena discussed above, but so far discussion of them has been omitted.

Eruptions through crater lakes.—Eruptions through crater lakes produce disastrous mud flows resulting in extensive deposits of volcanic breccia (volcanic conglomerates of Lacroix, Wolff, and others). Some of the Javanese and Antillean volcanoes give historical examples of this type of eruption. Lacroix (1904, pp. 176–179) was an eyewitness to an explosion through the crater lake at La Soufrière on St. Vincent Island, on March 3, 1903. According to his description, the water in the lake was quiet, with the appearance of yellow mud, the yellow color being

caused by oxidation. Suddenly without warning a vast mass of black mud containing blocks of rock was projected into the air 800 meters above the observers. The black mud soon settled back into the crater, causing a white cloud of steam to rise. In the course of four hours, several smaller explosions of the same kind occurred at irregular intervals, and Lacroix suggested that they were caused by violent gaseous explosions which brought up the mud of the lake. If the large explosion had been inclined rather than vertical, it would have passed down the valleys of the Wallibu or Rozeau, giving birth to a mud flow that would have reached the ocean. Mud flows did occur down these valleys from March 22 to 30, and Lacroix suggests this as the origin.

The disastrous Peléan eruption that destroyed St. Pierre on May 8, 1902, was preceded by violent mud eruptions from Étang Sec, a small crater to the north of the summit of Mont Pelée. Observations had shown that subterranean fissures carrying rain water had filled Étang Sec and a series of explosions had expelled all the material from the bottom of the depression. An enormous mass of thick mud carrying large blocks of rock descended into the valley of Rivière Blanche, destroying the Guerin Mills which were built at the river's mouth, and formed a headland in the sea of about 30 meters. This mud was hot but not burning. The emptying of Étang Sec was facilitated by the breaking of a dam from 20 to 30 meters wide.

The eruption of the volcano Klut, Java, in 1919, has given a recent example of mud flows of this origin (Escher, 1922; Brouwer, 1925, p. 77). During an average rest period of 18 years, the crater of Klut is filled with rain water, and new explosive eruptions must take place through the water of the crater lake. It is blown out of the crater mixed with hot ash, pumice, bombs, and lapilli, all of which flow down the slopes of the cone as a hot mud flow (the *lahar* of the Javanese). The greatest distance covered by such a mud flow was 38.25 kilometers with a breadth in part of 20.25 kilometers (Scrivenor, 1929, p. 434). An area of 131 square kilometers was covered by the mud-flow deposits, having a thickness of more than 50 meters in the upper course and a thickness of from 1.5 to 2.5 meters at the distal end. These *lahars* usually erode in the shorter and steeper part of the course and can only lay down deposits on the longer and more level part.

In a similar eruption at Galounggoung, Java, October 18, 1922 (Lyell, 1867, p. 56), hot mud containing ash and lapilli was carried to a distance 40 miles from the source. A space of 24 miles was covered with bluish mud, burying people in their houses. According to Verbeek and Fennema (1896, p. 234), 33 million cubic meters of water descended the mountain in an hour and a half, and when one adds the millions of cubic meters of "sand rock" that were carried along by the torrent, it is not astonishing that all the villages were destroyed in the valley below.

Collapse of the dam of a crater lake.—The collapse of crater lakes in the absence of explosions have given rise to cold mud flows (cold *lahars* of the Javanese). In January, 1875, the crater walls of Klut (Escher, 1925, p. 19) were ruptured and the water level was lowered 52 meters, forming a *lahar*. Escher (1925) has suggested this mode of origin for the deposition of a prehistoric chaotic assemblage of débris at the foot of Galounggoung, Java. In a sense, this is strictly non-volcanic, the only connection with volcanism being the location of a lake in a crater, and the effect would be the same as the breaking of the dam of any lake except that a large amount of pyroclastic material would be immediately available for transportation to lower levels.

Heavy rains falling on unconsolidated ejecta.—Lacroix (1906, p. 668) believes that mud flows rarely originate directly as a result of eruptions, and that other forces are responsible. His conception is that volcanic mud flows do not differ greatly from mud flows which occur in denuded mountainous countries, independent of all volcanic activity. As he points out, the special conditions on the flanks of a volcano in eruption are particularly favorable for their production, as a large quantity of incoherent material usually covers the surface, devoid of vegetation, and the atmospheric precipitation is generally more abundant than in normal times.

A la suite de chutes de pluies sur les hauteurs du volcan, les matériaux incohérents récents, poreux, absorbent une grande quantité d'eau; quand l'imbibition est suffisante, la masse tout entière se met en marche sur les pentes, dévale dans les vallées sous forme d'une *lave* épaisse, ... celle-ci s'avance souvent avec rapidité vers les régions basses, tenant en suspension des blocs énormes, érodant, entrainant tout sur son passage.

Sapper (1903, pp. 13–34) assigned a similar mode of origin to the mud flows in Guatemala, the removal of material being much more intense on the rainy south slopes. Where the rainfall was slight on the north slopes, the mantle of pyroclastic material was only removed in the neighborhood of creeks. The heavy tropical rains of Java also produce cold mud flows in the same manner (Brouwer, 1925).

Mud flows of a more or less similar origin constituted one of the most destructive post-eruptive features at Vesuvius in 1906. As previously described, a large amount of débris was removed from the upper slopes of the cone by hot avalanches.

The ash, sand, and boulders were in no case, however, carried more than 3 or 4 kilometers from the volcanic axis, and they remained consequently upon the slopes of the mountain. Rain or snow would then .... soak the porous mass until a certain consistency was reached, which conferred a degree of mobility differing widely in character from that of the hot avalanche, but nevertheless permitting rapid descent through gullies and other natural depressions as a torrent of liquid mud. This carried blocks and boulders of all sizes and constituted, through its volume and momentum, a peril second only to that of lava flows.—(Perret, 1924, p. 102.)

Mud flows of slightly different origin were observed by Hovey (1902, p. 327) on the island of St. Vincent. The accumulation of lapilli and dust from the Peléan eruptions retains its heat for a long time, and rain water from the tropical rains percolating through the beds comes into contact with the heated interior, causing explosions of dust-laden steam. On May 30, 1902, one of these explosions threw a dam across the stream of the Rabaka River, forming a temporary lake which soon cut through the dam, releasing the impounded water and sending a mud flow carrying large boulders down to the sea.

Showers caused by condensation of steam are commonly referred to as causing mud flows, but Koto (1916, p. 92) has questioned this after his studies on the eruption of Sakura-jima. He noted that the precipitation of rain always happened after an explosion, and not simultaneously with the ascent of the steam column from the main vents. He further states:

> In all the works on volcanoes, and in the chapters on volcanoes in geological and geographical textbooks, *showers* are mentioned as one of the usual attendant phenomena during eruption by electric discharges in the steam-column that ascends from the crater. *Mud-flows* ('moya' or 'frane') are mainly attributed to this cause. The writer for a long time hesitated to admit the correctness of this statement. There were no showers at the moment of explosion of Bandai-san in 1888. During the present activity the weather was fine from January 10 to February 8, excepting occasional mizzles which were no doubt caused by ascending clouds. During this long interval, all the phases of vulcanicity were in full display, and there must have been many opportunities present for cloud-bursts, if they really occur as usually stated in textbooks; but the writer never heard of, or saw any mud-flows excepting occasional ash-sleet, although the ash was abundantly deposited all around Kagoshima Bay.

Finch (1930*b*) has also questioned the condensation of steam as supplying heavy rainfall at the time of volcanic eruption. From observations of the explosions at Kilauea in 1924, Finch has shown that there was a good correlation between observed rainfalls and the relative humidity, so that the main source of rainfall accompanying an explosion is really the moisture of the surrounding air. But if the humidity is high, and other factors are favorable, we may have heavy rainfall at times of eruption that would aid in the development of mud flows.

Melting of snow and ice.—In regions of entirely different climatic character, mud flows are frequently developed by the melting of snow and ice caused by volcanic eruptions. The melting may be brought about by the extrusion of lava, the projection of *nuées ardentes* over snow- and ice-covered slopes, or by the simple eruption through ice and snow. The last cause is well exemplified in the Iceland mud flows, so well described by Thoroddsen (1906, pp. 171–172). These mud flows (termed *Gletscherlaüfe, Gletscherstürze,* and *jokulhlaup* by Thoroddsen) appear in great violence whenever a volcanic eruption takes place under

ice. The glaciers are broken and melted and a mixture of volcanic and morainic material is transported to the sea. If one looks at a map of Iceland, the southern margin of the island is characterized by a smooth shore line as contrasted to the fjord coast line of the remainder of the island. This has been brought about by mud flows that have filled the fjords and extended the coast line seaward. Within historic time dry land has emerged where formerly fishing boats anchored in 20 fathoms of water.

In the recent eruption of Tokachidake volcano, Japan (Tada and Tsuya, 1927, pp. 49–50), half of the northwest side of the cone collapsed at the time of a violent eruption and this immense amount of rock fragments, accompanied by steam, gas, and possibly hot water, suddenly melted the snow that had accumulated on that side of the mountain, forming disastrous mud flows that poured down its slopes. Twenty-five minutes after the eruption, the mud flow arrived at the town of Kami Fuiano, 24 kilometers from the crater, burying fertile valleys and farms.

The eruption of Cotopaxi, Ecuador, in 1877, is frequently cited as an example of mud flows formed by the melting of glacier ice by an extruded lava flow.

> Floods of water and mud. The sudden outflow of an enormous amount of fluid glowing lava over the volcanic cone covered with thick layers of ice and snow must have as a consequence the melting down of a great part of these layers. There were generated simultaneously around the whole circumference of Cotopaxi great masses of water that rushed down its steep slopes as torrents or cataracts. . . . .
>
> The glowing lava, although in the uppermost parts discharged with force over gullies and crests and often across ridges, must soon collect in great masses in the broad troughs and push downward in them. In consequence enormously broad and deep channels were furrowed out in ice and snow, and great streams of water generated. Observation has shown me in the clearest manner that the water and mud masses (the so-called *avenidas*) in every single gulch stand in relation to the channels excavated in the ice above them as their direct prolongation, and further that the channel, for its part, is related to the lava mass (the "lava mass," as later described, is composed of fragmental material) that came down through it. This observation is important for the correct explanation of the floods of water and mud. Only one or two small gulches on the northeast side of Cotopaxi were fortuitously spared from the avenidas, all the rest were more or less heavily filled with them. . . . .
>
> In the upper and middle parts most of the gulches, although narrow, were deep enough to hold the stream, but where they come out on the more gently inclined plains and possess no high banks, it poured without limit over fields, pastures, haciendas, roads, etc., destroying and carrying everything away with it. From Callo to Latacunga the plain presented the appearance of a great lake of mud in wildest agitation.—(Wolf, 1878, pp. 133–135; translated by Fenner, 1923, p. 11.)

According to Whymper (1892, p. 123), this flood reached the village of Esmeraldas, situated 150 miles from the crater, but the flood followed a more circuitous route, probably doubling the actual distance covered.

The average rate of movement was about 17 miles an hour. Toward the base of the mountain, the rate was estimated to be about 50 miles an hour.

Wolf's account of the eruption is based principally upon the statements of eyewitnesses and his own observations following the eruption. Fenner has suggested from reading Wolf's account, that although Wolf assumed that the extrusion was liquid lava, the account given by him points strongly to a Peléan eruption.

> Wolf's description of the eruption reminds one of the characteristics of nuées ardentes much more than of ordinary flows of liquid lava .... the black mass suddenly boiling up and overflowing the rim of the crater on all sides, the prodigious speed with which it precipitated itself down the slopes, the great mass and short duration of the flow, the heavy clouds concealing the mountain within a few minutes, the rain of ashes immediately afterward, the carbonization of tree trunks, the lack of coherent lava flows, the forcible manner in which the outburst spread over valleys and ridges on the upper part of the cone and later flowed down gulches in a more collected form—these point almost irresistibly to this form of eruption.—(Fenner, 1923, p. 67.)

According to Day and Allen (1925, pp. 20–24), the mud flows which developed on the east side of Lassen Peak, May 19, 1915, were also formed by *nuée ardente* eruptions accompanied by ash and condensed steam, melting the accumulated snow banks so that torrents of mud rushed down the slopes of the mountain. Finch, however, has questioned the power of falling ash and rain to melt an appreciable quantity of snow.

> The behavior of rain on snow is worthy of some discussion. A few feet of snow of uniform covering can absorb several inches of rainfall so that the rain produces but little immediate run-off. If there had been bare spots in the snow field, water could have accumulated so as to run under the snow in considerable quantities, in caverns and in a place as steep as the Lassen slope, might have undermined so as to start avalanches. A hot blast unless long continued, or a slight deposit of volcanic ash would produce the same effect as rain .... a melting of superficial layers of snow and an absorption of the water by lower layers. A hot blast or a hot ashfall on a steep slope not uniformly covered with snow, could start streams under the snow as in the case of rain, and might thereby cause avalanches.—(Finch, 1930*a*.)

Finch presents evidence to show that a large volume of hot lava poured over a notch in the eastern side of the crater, and that much of this new lava was carried down in fragments with the mud flow.

> The lava flow could easily have melted the snow down to the ground and have sent a stream of warm water under the snow lower down the slope. An avalanche mixed with hot rock could have started in this way and might have produced a flood of the magnitude observed, if great snow drifts were present.—(Finch, 1930*a*.)

Finch has omitted one possibility in the general consideration of the melting of snow by hot blasts (*nuées ardentes*), and that is the possibility of great masses of snow and ice being picked up in the upper course and melted while in transit. From the present state of our knowledge

regarding *nuées ardentes*, it is doubtful whether they can be eliminated as a factor in causing large mud flows through the melting of snow and ice.

Under favorable conditions, we may have the rapid melting of snow and ice in the absence of volcanic action, yet producing mud flows similar to those described above. Mud Creek on the eastern side of Mount Shasta, California, has cut a deep canyon through beds of poorly consolidated pyroclastic rocks with a few interbedded lava flows. Mud Creek derives its water from the Konwakiton Glacier, and every summer, at the time of maximum melting of the snow and glacier, Mud Creek always carries more or less mud, derived by undercutting the unstable walls with resulting landslides. During summers of very warm weather following winters of limited snowfall, the Konwakiton Glacier melts very rapidly, supplying a large amount of water to Mud Creek which in turn picks up an increasing amount of débris from the walls of the canyon. By the time the water reaches the lower slopes of the mountain, a thick mud flow has developed which spreads out at the base of the mountain. Mud flows of such character developed during the summers of 1924, 1926, and 1931, and there is abundant evidence of many earlier ones.* In these mud flows where the material is derived from pyroclastic rocks, it is impossible, from the deposit alone, to distinguish this type of origin from the others described above.

Eruptions following heavy rains.—Hot mud flows occurred during the recent eruptions of Santa Maria, Guatemala. Although no systematic observations were made, Sapper and Termer (1930) have reconstructed the sequence of events from the statements of eyewitnesses. Mud covered an area 10 kilometers long and varying from 100 meters to one and a half kilometers wide. Blocks or rocks 20 cubic meters in size and not appreciably rounded, occurred in the midst of this field, while stumps of trees were carbonized. The inner part of this flooded mass was hot for four weeks. The evidence points to a Peléan eruption, but, unlike those of Martinique, the eruption followed the end of the rainy season in a rain-rich region and the streams were high. The glowing rocks and dust were shot into the rivers, heating the water and forming a mud flow which, spreading over the land, filled the valley with a deposit of hot mud.

* From observations made by R. H. Finch and the writer in the summer of 1928.

DISCUSSION AND CONCLUSIONS

From the above descriptions of how volcanic breccias may be formed, the difficulty of limiting the origin of the Tuscan breccias to one or two possibilities becomes readily apparent. The writer has given reasons for objecting to the explanation of the Tuscan breccias by any dry method. Most of the breccias falling in Class I (page 246) that have formed within the last century and that have been described, are much more local in their distribution than the Tuscan breccias. The large areal extent and low angle of repose of the Tuscan breccias are almost sufficient to eliminate all the possibilities of this class. But when we turn to a consideration of Class II, volcanic breccias formed by the aid of water (mud flows), we find many facts that are applicable to the Tuscan breccias.

In comparing the deposits of mud flows to those of *nuées ardentes,* Lacroix (1904, p. 380) stated that they are somewhat similar except that the blocks in the latter are less rounded and that pumice is not penetrated by the fine mud as in the mud flows. Also, intercalations of stratified beds are common features in deposits of mud flows. In the Tuscan breccias, pumice is conspicuously absent, so that the infiltration of mud cannot be used as a test.

The eruptions of Lassen Peak give some interesting comparisons between mud flows and *nuées ardentes,* for the mud flow of May 19, 1915, was followed by a Peléan eruption on May 22. Mud filled a house to the window sills at Old Station, 20 miles from Lassen Peak, on May 19, while the effects of the *nuée ardente* were only noticeable for a distance of four miles (Day and Allen, 1925).

The distances traveled by the following mud flows are of interest:

Galounggoung, Java	1822	40	miles
Cotopaxi, Ecuador	1877	150	miles (probably twice this distance because of the circuitous route)
Klut, Java	1919	38.25	kilometers (24 miles)
Mount Shasta, California	1924	12	miles
Tokachidake, Japan	1926	24	kilometers (15 miles)
Santa Maria, Guatemala	1929		Area covered by mud for a distance of 10 kilometers (6.2 miles)

The mud flows of Iceland, Martinique, and St. Vincent all ended at the sea, and the distances traveled are small. Of course the distance traveled by a mud flow is largely determined by the slope angle and volume of water; the only purpose of the above table is to indicate that recent mud flows have traveled distances comparable with the linear extent of the Tuscan breccias. Considering the open country with an average slope of 2°–3° in the lower part, and given a sufficient volume to initiate the flow, it seems a reasonable supposition that the Tuscan mud flows brought down the débris from the higher parts of the Lassen region. Of course, many of the mud flows did not travel great distances,

as is shown by the thick deposits of breccia near Lassen Peak. Only occasional mud flows reached the greater distances.

The ease with which mud flows transport large blocks has been emphasized by many writers. This ease of transportation is not surprising when one considers the relatively high specific gravity of the liquid transporting these large blocks. Blackwelder (1928) has discussed nonvolcanic mud flows as they occur in semi-arid regions, but, since mud flows are practically the same regardless of their origin, some of his statements are pertinent to our discussion. He has found that the slope need not be steep if the material and water supply are unusually favorable. One of the characteristic features of mud-flow deposits is the unassorted and unstratified character of the material, while flood deposits normally assort their loads to some degree and leave their deposits perceptibly stratified. The large boulders that are carried by these muds do not settle to the base, but even lie on the flow itself. The absence of appreciable abrasion of the large blocks is striking, but since the blocks appear to float more or less, the chance to become abraded is reduced to a minimum. As Blackwelder (1928, pp. 472–473) states:

> The mud flow contains just enough water to swell the clay colloids, reduce internal cohesion, and make the mass slippery..... In most respects the mass behaves much like a lava flow. In its ability to carry large boulders on its surface it bears some resemblance to the still more slowly moving glacier. Observers are not wholly agreed as to how the mass moves, but the various phenomena indicate that it slides or glides over the surface without that internal churning that characterizes a rapid stream of water.

When this factor is considered, it may be seen that abrasion will be reduced to a minimum. A photograph of Blackwelder's (1928, fig. 7, p. 477) illustrates the angular character of the mud-flow deposits.

Rickmers (1913, p. 193) has described a mud flow as follows: "It is neither dry nor is there much free water, but the whole mass appears like a rapid flush of mud, although frequently the rock waste is so rough as not to suggest what is popularly called mud. Enormous boulders will float in this thick porridge like cork on water or iron on quicksilver."

As to the origin of the mud flows that deposited the breccias of the Tuscan formation, there is a lack of suitable evidence suggesting any one of the possibilities, and it may very well be that a number of mud flows of various origins may have contributed to their deposition. The Javanese mud flows are quite commonly the result of explosion through or the collapse of crater lakes. One of the striking features of the Javanese volcanoes is the number of crater lakes, probably caused in large part by the heavy tropical rainfall. But it would require a large number of refillings of crater lakes to supply the necessary water, as a little speculation on the immense amount of material in the Tuscan breccias will quickly reveal.

The paleobotanical evidence does not suggest a climate of heavy rainfall in the region during the Pliocene. According to Dorf (1930, p. 57), the Pliocene floras indicate the presence of mountain ranges in the Pliocene, which had the effect of producing a distribution of vegetation similar to that now present in California. The climate would correspond more or less with that of the present in the same general region, that is, approaching semi-arid conditions and a tendency toward coolness rather than warmth.

In the absence of heavy rainfall, the hypothesis of crater lakes as the source of water for the mud flows becomes doubtful, while comparison with the present climate immediately suggests the accumulation of snow and ice which might supply the necessary water. The peaks in the general latitude of Lassen Peak above 9000 feet elevation usually accumulate noticeable snow banks (pl. 20*b*), many of which last through the summer. Mount Shasta, with an elevation of 14,000 feet, has five glaciers at the present time, so it is quite probable that the volcanoes supplying the débris of the Tuscan formation were heavily mantled with snow and ice and possibly glaciers. The suggestion of the melting of snow and ice, by both volcanic and non-volcanic phenomena, appears reasonable in spite of the lack of positive evidence supporting it. Turner (1896, p. 53) has suggested the same origin for the andesitic breccias of similar character that cover the slopes of the Sierra Nevada to the south. Dr. Ralph Chaney* has suggested that the Upper Pliocene was becoming cooler in preparation for the cold Pleistocene, so it seems reasonable to suppose that conditions would be favorable for the accumulation of snow and ice.

Combinations of some of the phenomena discussed above may have given rise to the Tuscan mud flows. Although the eruption of Bandaisan was essentially that of a dry-rock avalanche, during its descent part of the débris mingled with the water of lakes and ponds that it encountered so that it acquired a muddy character in the lower part of its course and this may have assisted in its flow. Also new lakes were formed, owing to the damming up of rivers by débris, and the collapse of these dams suddenly released a large amount of water that rushed through the avalanche deposit, carrying mud and boulders to lower levels.

*Oral communication.

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EXPLANATION OF PLATES

PLATE 17

a. Overhanging cliff at contact of two beds of tuff breccia. Antelope Creek, south of Tuscan Springs.

b. Pillar of breccia. Battle Creek, 10 miles west of Mineral.

c. Tuff breccia above volcanic conglomerate. Chico Creek.

d. Fine breccia overlying massive tuff. Antelope Creek, south of Tuscan Springs.



a



c



b



d

PLATE 18

a. Volcanic gravel and sand. Chico Creek.

b. Water-worn cobbles in tuff breccia. South of Millville.

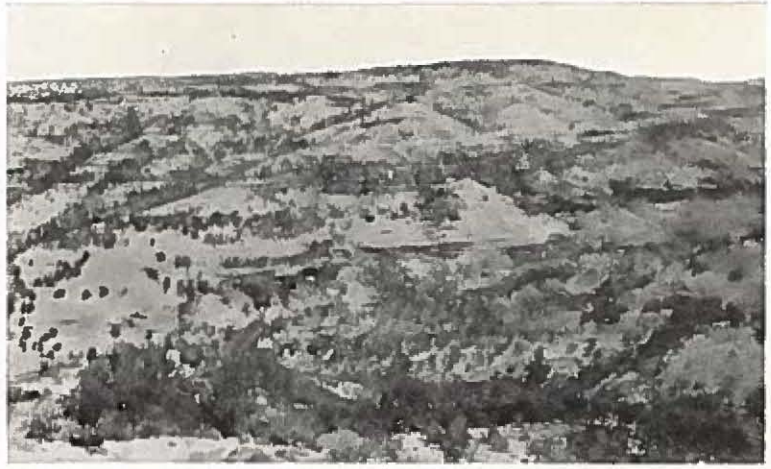
c. Stratification of the tuff breccias. Mill Creek (fig. 3, no. 13).

d. Terrace developed on upturned Tuscan beds. At the gap of Mill Creek.

rock.



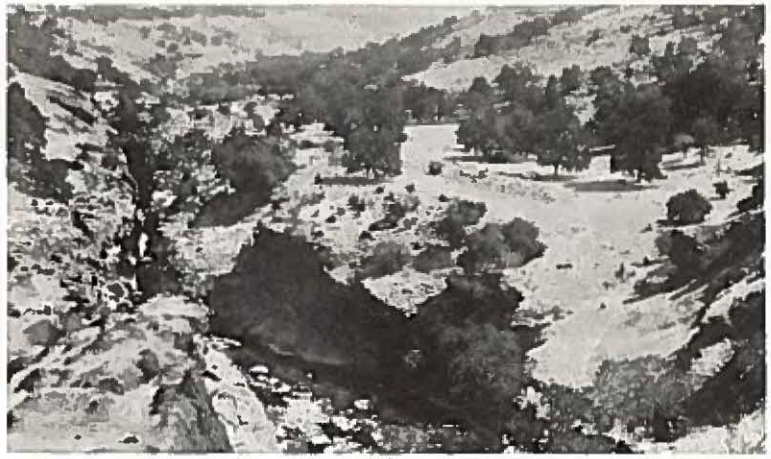
a



c



b



d

PLATE 19

a. Iron Canyon, north of Red Bluff. Stratified volcanic sands and tuffs with massive tuff breccia at the top. Tuscan Buttes in the background and Tuscan Springs arch to the right. Photographed by Dr. N. E. A. Hinds.

b. Block imbedded in tuff breccia, Iron Canyon. Abraded by flood waters of the Sacramento River. Photographed by Dr. N. E. A. Hinds.



a



b

PLATE 20

a. Concentration of blocks on the surface resulting from rain wash and wind action. Basalt flow in the background outlined by dense growth of trees. Ten miles east of Red Bluff. Photographed by Mr. R. H. Finch.

b. View toward Lassen Peak and Brokeoff Mountain (peak to the right) from Tuscan Buttes. Inskip Hill in the middle ground. Photographed by Mr. R. H. Finch.



a



b

PLATE 21

Pillar developed in breccia and tuff breccia. Vertical jointing apparent across the valley. Battle Creek, 10 miles west of Mineral. Photographed by Mr. H. C. Lind.

