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# LATE TERTIARY FLORAS AND THE SIERRA NEVADAN UPLIFT

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## ABSTRACT

Twenty-one Mio-Pliocene floras distributed from sea level in west-central California, across the Sierra Nevada and into western Nevada, are preserved in volcanic sediments occurring either (1) at or near the base of the andesitic Mehrten formation and its correlatives east and west of the Sierra Nevada, or (2) in the underlying rhyolitic Valley Springs formation and its close equivalents in western Nevada and coastal California. Since the floras are related to living communities whose topographic and climatic relations can be measured, they provide a basis for estimating the altitude of the Sierra Nevada and of west-central Nevada at the inception of vulcanism during Mio-Pliocene time. Local, provincial, and regional comparisons indicate that there were then only moderate east-west differences in vegetation, climate, and topography across this area where environmental diversity is marked today.

A number of paleogeographic inferences are made: *Geologic*—Just before late Tertiary vulcanism the Sierra Nevada was a broad ridge with its summit near 3000 feet. It was incised by 2- to 4-mile wide, 1000-foot-deep valleys, some of which drained western Nevada. The lowlands of western Nevada had an average elevation of 2000–2500 feet. Two major components of late Cenozoic diastrophism are recognized in the Sierra Nevada. Faulting accounted for an average maximum displacement of 3500 feet in this section of the range, and regional warping ranged from 1800 feet at Donner Pass to 3000 feet at Carson Pass 50 miles south. *Climatic*—Building up the Sierran ridge from 6000 to 8000 feet by vulcanism and diastrophism in the later Cenozoic (1) reduced temperature along the summit so that arctic-alpine and subalpine forest environments came into existence, and (2) lowered rainfall sufficiently over the lowlands to leeward to account for the present steppe (sage) and desert regions. *Biologic*—Plants (and animals) from contiguous milder environments gradually were invading these new zones during the later Cenozoic and have continued to evolve there.

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## The Problem

The northern and central sections of the Sierra Nevada and the adjoining parts of Nevada are blanketed chiefly by upper Tertiary volcanics and associated sediments. An important hiatus separates them from the underlying section, most of which is a basement of metamorphic and granitic rocks, though Eocene and Oligocene rocks are represented locally. The upper Tertiary volcanics locally exceed 3500 feet in thickness and rest on a surface of low to moderate relief. The section has been folded and faulted, with total displacement along the north-central portion of the Sierran scarp averaging 3500 feet during late Pliocene and Pleistocene times. Therefore, what was the elevation of the range and of the easterly bordering area just before the extensive rhyolitic and andesitic eruptions near the close of Miocene time, following a long period of erosion?

This problem has earlier attracted the interest of geologists. Lindgren (1911), in particular, discussed the evidence provided by the gradients of the Tertiary Sierran stream channels and concluded that the summit of the range was between 5000 and 7000 feet in Miocene time. This excessive estimate resulted from three misconceptions. First, Lindgren thought that the broad channels containing the auriferous gravels (by which he calculated the stream gradients) and the overlying volcanics were all the same age, namely Miocene. It is clear now that most of the older gravels are part of the Ione formation of early Eocene (Capay) age (Allen, 1929; MacGinitie, 1941), and that a major hiatus separates them from the volcanic section comprising the Valley Springs and Mehrten formations which range from Mio-Pliocene well into Pliocene time. Lindgren's data on the gradients of the stream channels thus relate to the profiles of the Eocene rivers, not to those of late Tertiary age. As shown by Hudson (1955, p. 855), a discordance between the Eocene and Mio-Pliocene rocks indicates that some deformation had taken place during this interval, at least locally in the range.

Secondly, Lindgren's data on the gradients of the channels are subject to error. His sections suggest that both folding and faulting took place within the range in subsequent times, yet in determining the original stream gradients he did not compensate for structure. Following the views of King, LeConte, and others, he believed that the range had reacted substantially as a rigid block (Lindgren, 1911, p. 48). Hudson (1948; 1951; 1955) has shown, however, that folding and faulting were important in the late Tertiary history of the range, not only in the summit section, but also within the range.

Finally, by a peculiar line of reasoning which was colored in part by his erroneous comprehension of the structure of the range, Lindgren concluded that the streams started on a drainage divide that lay a few miles west of the present one. Actually, some of the gold-bearing channels which he thought headed in the range extended eastward into Nevada (Reid, 1911; Gianella, 1936). His estimate of a 5000- to 7000-foot crest for the central to northern Sierra Nevada in the early Tertiary is too high, as shown by the regional relations of the Eocene floras in the far West.

Matthes (1930) also made an estimate of the height of the central part of the range in connection with his study of the Yosemite area. He pointed out that an old erosion surface (the broad valley stage) carved into the crystalline rocks could be traced from Yosemite Valley into the summit region, as well as northwestward in the range for 40 miles where it lay covered by the andesitic Mehrten formation near Tuolumne Table Mountain. He dated this surface late Miocene (here considered Mio-Pliocene), for at Table Mountain plants (Table Mountain flora) and mammals (Springfield Shaft local fauna) of this age occur at the base of the volcanic section. Matthes then pointed out that the erosion surface had an elevation of approximately 4000 feet in the Yosemite summit region in Mio-Pliocene time.

This figure was obtained by asserting that uplift at the end of the Miocene added 3000 feet to the range and that faulting at the close of the Tertiary increased the height of the block by an additional 6000 feet. The sum of these subtracted from the present summit level of 13,000 feet gives the figure of 4000 feet.

A number of objections concerning Matthes' interpretations have been raised. Some geologists have expressed skepticism that the upland surface in the Yosemite area corresponds to that on which the Mehrten formation was deposited. They point out that there is no evidence that the Yosemite area was covered by andesite, and hence the erosion surface may have been developing since Miocene time, or earlier; in any event, the present surface is of later Cenozoic, not of Mio-Pliocene age, for it is not covered by volcanics. Others have examined the region and doubt that there is an old erosion surface, at least in Matthes' sense.

Of greater importance to the problem of elevation, however, is that Matthes cited no facts in support of Mio-Pliocene faulting in the Yosemite area. Actually, no such evidence exists there, for the rocks in the uplands are pre-Tertiary crystallines and provide no data for estimating the amount of faulting at any time in the Tertiary. His estimate of 3000 feet uplift of the close of the Miocene apparently was derived from the work on the Truckee quadrangle which led Lindgren (1897) to believe that there was major pre-andesite faulting in the region. Although there is evidence of faulting during the short interval between the accumulation of the Valley Springs and Mehrten formations, as at Donner Pass (Hudson, 1948; 1951), it was relatively minor. This Mio-Pliocene faulting does not account for the Tahoe graben, as Lindgren supposed; it is much younger. Recent work by Garniss Curtis (September 1955, personal communication) in the area from Carson Pass to Ebbets Pass, 50 to 65 miles south, has failed to demonstrate the existence of major pre-andesite faulting in that broad region. To suppose that large-scale faulting took place in the Yosemite region another 70 miles south in Mio-Pliocene time seems unwarranted. Thus, whereas Matthes' estimate of the altitude of the summit region is not greatly different from that provided by the paleoecologic analysis presented below, the method by which his conclusion was reached is unsound.

Hudson (1955) measured post-Eocene deformation in the Sierra Nevada by using the gradients of the Tertiary Yuba River which are marked by the old auriferous gravels that can be traced from sea level into the summit area. Rather than relying on the gradient of the complete stream course, which has been warped and faulted, Hudson chose several triplets (three consecutive reaches of the channel) for study. The method, he points out (1955, p. 850),

> "... *does not yield the actual original gradient of a triplet of reaches, but what the original gradient would have been if the three reaches had a common gradient and lay on a block that remained rigid during tilting.* In order to learn the probable effect of lack of equality of the original gradients of the members of the solved triplets, one must first decide upon the probable amounts of variance from equality. This was done by studying parts of the modern Yuba river where the gradients approximate those for the eight usable triplets of the ancient stream."

Hudson concluded that the Sierran summit was 5500 feet in the early Eocene (1955, Fig. 2B) and that total uplift of the summit region at Donner Pass has been only 1986 feet since that time. These results do not agree with the evidence of altitude supplied by the late Tertiary floras in the near-by Sierra Nevada and adjacent Nevada. They suggest that the range was the site of a broad low ridge at the close of Miocene time, and that in the Donner area uplift has been on the order of 5300 feet since the middle Pliocene.[1]

ACKNOWLEDGMENTS

This study is one of the results of a long-term investigation of late Tertiary paleobotany in the far West. The project has been supported by the Carnegie Institution of Washington, the National Research Council, the Committee on Research, University of California, Los Angeles,

[1] Hudson and the writer have discussed their different interpretations more than once. In his latest letter (Oct. 12, 1955) he states: "One or the other of us is wrong, or both of us are wrong in greater or less degree. I think your course should be, not to try to reconcile the results, but to state that the paleobotanic evidence indicates that my estimate is too small."

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The manuscript has been read critically by George A. Bartholomew, Ralph W. Chaney, Garniss Curtis, Erling Dorf, Cordell Durrell, Carl Epling, Frank S. Hudson, Harry D. MacGinitie, William C. Putnam, and Edward L. Winterer. They have added to its clarity and made several important suggestions which have been incorporated in the discussion.

## METHOD

Fossil plants have been used repeatedly to interpret the nature of ancient topography, especially during Cenozoic time because most Cenozoic plants closely resemble living species whose present requirements in terms of terrain and climate can be analyzed. Although one plant may provide evidence of past environment within broad limits, sounder results are obtained by comparing fossil floras with modern communities which resemble them most closely. In this way details of relief and climate surrounding a basin of deposition can be outlined with reasonable accuracy. Comparisons of floras of similar age over wider areas permit inferences of broader paleogeographic significance.

The interpretation of ancient relief, particularly its bearing on altitude, falls into two categories—local and regional. In a local problem the difference in elevation between the environment indicated by the fossil flora and the modern flora at the site of deposition is determined as nearly as possible. For example, Puri (1947) studied the rich Pleistocene Liddarmarg flora which occurs at 10,600 feet in the foothills of the Himalayas. It contains numerous warm-temperate or subtropical plants whose upper altitudinal limits now lie from 4000 to 6000 feet lower than the basin of deposition. He concludes that since the beds were deposited the range has been uplifted on the order of a mile.[2] Berry (1917; 1922a; 1922b; 1938, p. 49–51) described several fossil floras from the mountains of Bolivia which occur at elevations of more than 12,000 feet. They contain subtropical and tropical plants similar to those living today at much lower altitudes. He concluded that the Andes must have been elevated a mile or more in this area during the late Cenozoic, bringing these localities into a cold high-altitude desert climate where the vegetation is very different. MacGinitie (1953) showed that the rich Florissant flora, preserved in lake beds in central Colorado at an elevation of 8500 feet, is a mixture of plant communities whose general ecological relations suggest that this Oligocene basin was no higher than 3000 feet and was probably lower.

In regional studies, comparisons of fossil floras of similar age that now lie on opposite sides of a high mountain range may demonstrate that the present intervening barrier could not have existed when the floras were living. Berry (1922c) pointed to the marked differences between the present temperate rain-forest climate on the coastward slopes of the high Andes in southern Chile and the cold desert climate of Patagonia to leeward. He found that the warm-temperate flora associated with the Eocene Concepcion-Arauco coal beds in southern Chile (Berry, 1922c) resembled the Rio Pichileufu flora across the Andes in Patagonia (Berry, 1938) and concluded that the range was not yet a major climatic barrier when these floras were living (Berry, 1938, p. 53). In the same way, Chaney (1938a; 1938b) noted that the Cascades now separate widely different environments in Oregon: humid-temperate conifer forests densely blanket the windward side of the range and open semiarid sage and desert communities occur over the lowlands to leeward. By contrast, the Eocene subtropical lowland forests of interior Oregon are closely related to those of the western coastland. Such similarities of vegetation

[2] In this example, Puri did not consider the possibility that during the Pleistocene climatic change alone may have accounted for the shift of a lowland flora into the uplands, or vice versa.

and the climate inferred suggest that the Cascade range did not exist as a high topographic barrier in Eocene time.

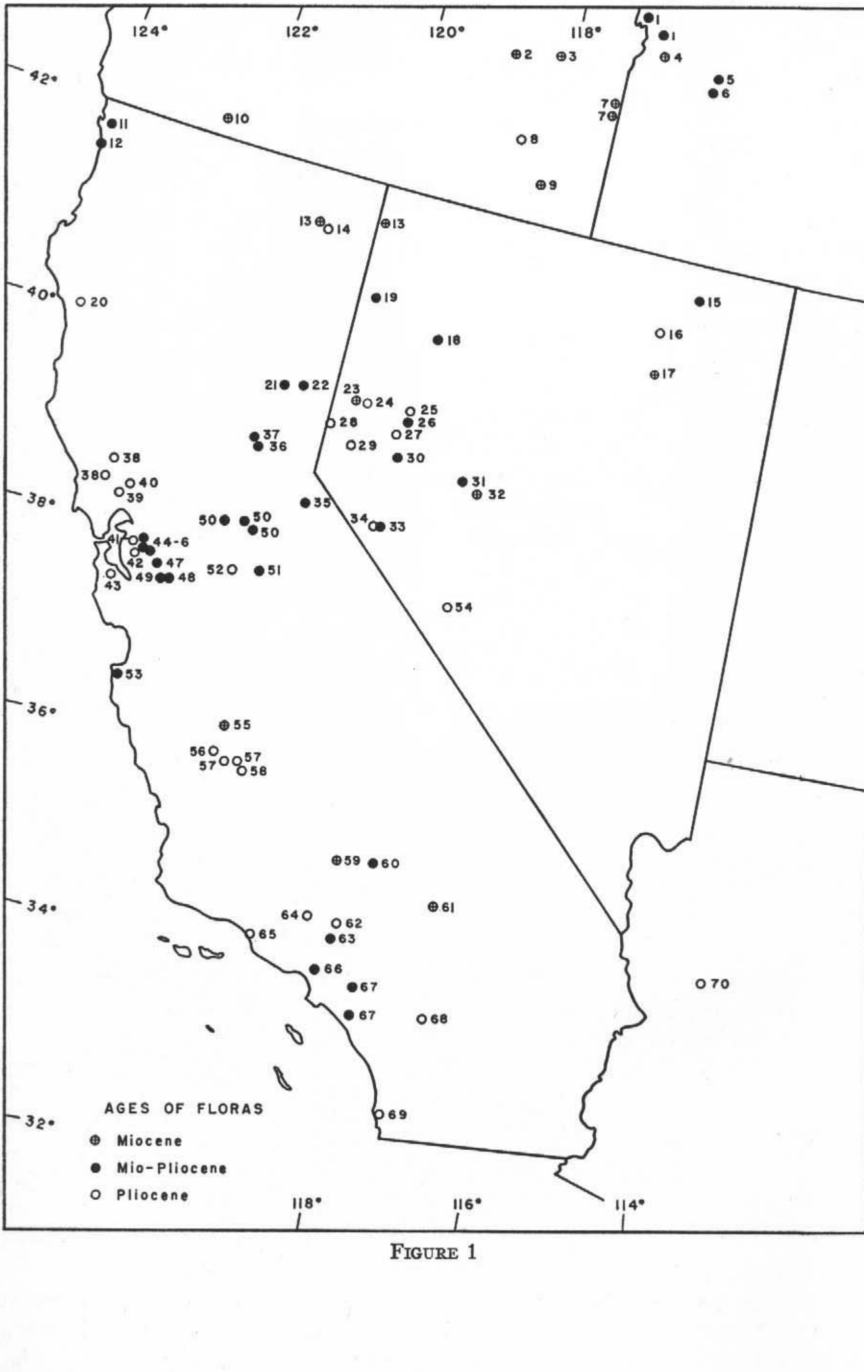
Comparisons of floras of similar age on both sides of a mountain range may show sufficient differences in vegetation, and the climates they suggest, to indicate that the range was already beginning to rise. Chaney (1944b, 358–360) compared the early Pliocene Troutdale and Dalles floras from the windward and leeward sides of the Cascades in northern Oregon at the latitute of the Columbia River. The differences between them suggest precipitation was approximately 10 to 15 inches less in the lowlands to the east of the ancestral Cascades. This is paralleled by modern relations in the Coast Ranges of California, where ridges 1500 to 1700 feet high account for similar differences in related vegetation and climate on their windward and leeward slopes. Thus Chaney suggests that the central Cascades may have had a similar elevation in the early Pliocene.

These local and regional methods of analysis are used here to estimate the altitude of the Sierra Nevada and the plateau which lay to the east of it during the late Tertiary. First for analysis is a group of Mio-Pliocene floras (early Clarendonian, Neroly-Cierbo, late Mohnian-Delmontian ages) that extend from sea level in coastal California across the Sierra Nevada and into western Nevada, supplemented by data from floras of similar age to the north and south. They will indicate the relative altitude of the region at the outbreak of vulcanism in Mio-Pliocene time. A number of Pliocene floras in the area are then referred to in the section on paleogeography, for they have an important bearing on later topographic, climatic, and biologic changes in the region. Before discussing the paleobotanic evidence, however, the stratigraphic occurrence of the floras must be summarized briefly.

## Stratigraphy

In recent years studies of numerous late Tertiary floras in west-central California and in the Sierra Nevada have been completed (Chaney, Condit, and Axelrod, 1944); Axelrod, 1950a); studies of other floras are in their final stages (Axelrod, in press; MSS), and others have been collected and studied sufficiently so that preliminary conclusions can be drawn with respect to their ages and the environment in which they lived. Figure 1 shows that more than 35 floras of middle and late Tertiary age occur in the area from sea level in central California across the central Sierra Nevada into western Nevada, and that others lie to the north and south. More than 20 of these floras lived in the late Miocene or early Pliocene. There is still much overlap in the usage of these terms on the Pacific Coast, though the time dealt with here can be delimited precisely in provincial ages. Many of the floras occur in rocks that have yielded mammalian faunas of early Clarendonian age, which most vertebrate paleontologists regard as early Pliocene (Wood *et al.*, 1941). Others come from beds associated with marine megafossils which represent the Cierbo and Neroly "stages" of the marine molluscan sequence and are commonly considered late Miocene (Weaver *et al.*, 1944), though they have also yielded early Pliocene mammals. Some of the floras are in rocks containing marine microfossils that range from the Mohnian into the Delmontian, regarded generally as late Miocene and Mio-Pliocene, respectively, (Weaver *et al.*, 1944). These rocks have also yielded late Miocene mollusks and in some places interfinger with beds containing early Pliocene mammals. This diversity in the usage of epoch terms on the Pacific Coast is due in part to correlation problems and in part to the fact that the type sections of the Miocene and Pliocene are not continuous. Described from different areas, they are separated by a hiatus that is apparently equivalent to the European Pontian and Sarmatian stages, and to the Barstovian (upper), Clarendonian, and Hemphillian North American mammalian stages. Since there is no agreement on where the Mio-Pliocene boundary should be placed, the floras studied are considered Mio-Pliocene. Their temporal relations are summarized in Figure 2.

There is still much confusion in recent literature concerning the age and stratigraphic relations of the Tertiary rocks in the Sierra Nevada. Since the present problem involves the regional relations of some of these forma-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AGES OF FLORAS
Miocene
Mio-Pliocene
Pliocene

FIGURE 1

tions, the Tertiary stratigraphy in the central and northern parts of the range is summarized here (Fig. 3). The diverging lines for the epoch boundaries represent current opinions of the relation of the west-coast stages to the European section. The post-Paleocene epoch boundaries drawn by the mammalian paleontologists fall at the bases of the Wasatchian, Chadronian, Arikareean, and Clarendonian stages, and at the top of the Blancan. The molluscan correlations with the European epochal boundaries are shown by the lines on the right side of the epoch column: the boundaries are at the bottom of the Capay, in the upper third of the Keasey, the middle of the Blakeley, the base of the Jacalitos, and the top of the San Joaquin.[3]

It is apparent that the Mio-Pliocene floras of the Sierra Nevada were living just before or during the early eruptions of the late Tertiary andesites which are termed the Mehrten formation in the Sierra Nevada and the Kate Peak to the east. This is an important stratigraphic position, for in the Sierra Nevada the base of this andesite section at a number of localities is accurately dated as early Clarendonian by mammalian faunas (*Springfield Shaft*— Marriam and Stock, 1933; *Two-Mile Bar*— Stirton and Goeriz, 1942) and floras (*Table Mountain*— Condit, 1944b; *Remington Hill*— Condit, 1944a; *Forest*— Condit, 1944a, p. 38; *Mohawk*— Axelrod, 1944, p. 220–221). The late Tertiary andesites, which were erupted chiefly in the upper parts of the range and to the east in Nevada, were transported to basins which lie farther east and west. Significantly, a fauna of early Clarendonian age occurs at Coal Valley in western Nevada (Stirton, 1939b, p. 634), where it is associated with the lowest Kate Peak andesites (Axelrod, in press). The andesites transported westward across the Valley of California have been found and recognized in the San Pablo (Neroly) formation at Corral Hollow (Louderback, 1924; Huey, 1948), where they interfinger with a marine section. A large flora occurs in the andesitic sandstones at Corral Hollow (Lesquereux, 1883; Condit, 1938); marine megafossils of Neroly age and marine microfossils of Mohnian-Delmontian age are also represented in this section, as are mammalian fossils of early Clarendonian age (Stirton, 1939a, p. 364–365). Thus the lower parts of the Mehrten and Kate

[3] The 18th International Geological Congress recommended that the base of the Pleistocene be placed at the bottom of the Villafranchian; thus on the West coast the base of the Pleistocene probably would fall near the middle of the Blancan and San Joaquin (Fig. 3).

FIGURE 1.—GEOGRAPHIC OCCURRENCE OF MIDDLE AND LATE TERTIARY FLORAS IN CALIFORNIA, NEVADA, AND BORDERING AREAS

Fossil Floras

1. Lower Idaho
2. Stinking Water
3. Beulah
4. Payette
5. Idaho City
6. Thorn Creek
7. Succor Creek
8. Alvord Creek
9. Trout Creek
10. Grizzly Peak
11. Wimer
12. Crescent City
13. Upper Cedarville
14. Alturas
15. Copper Basin
16. Humboldt
17. Elko
18. Rabbithole Springs
19. Juniper Valley
20. Wildcat
21. Monte Cristo
22. Mohawk
23. Pyramid
24. Quail Creek
25. Truckee
26. Chloropagus
27. Hazen
28. Verdi
29. Chalk Hills
30. Fallon
31. Middlegate
32. Buffalo Canyon
33. Aldrich Station
34. Coal Valley
35. Carson Pass
36. Alleghany
37. Remington Hill
38. Sonoma
39. Petaluma
40. Napa
41. Mulholland
42. Black Hawk Ranch
43. Santa Clara
44. Diablo
45. Loma Ranch
46. Bailey Road
47. Altamont Pass
48. Corral Hollow
49. Cierbo
50. Valley Springs
51. Table Mountain
52. Oakdale
53. Carmel
54. Esmeralda
55. Temblor
56. Jacalitos
57. Etchegoin
58. San Joaquin
59. Tehachapi
60. Ricardo
61. Barstow
62. Anaverde
63. Mint Canyon
64. Piru Gorge
65. Pico
66. Modelo
67. Puente
68. Mount Eden
69. San Diego
70. Wikieup

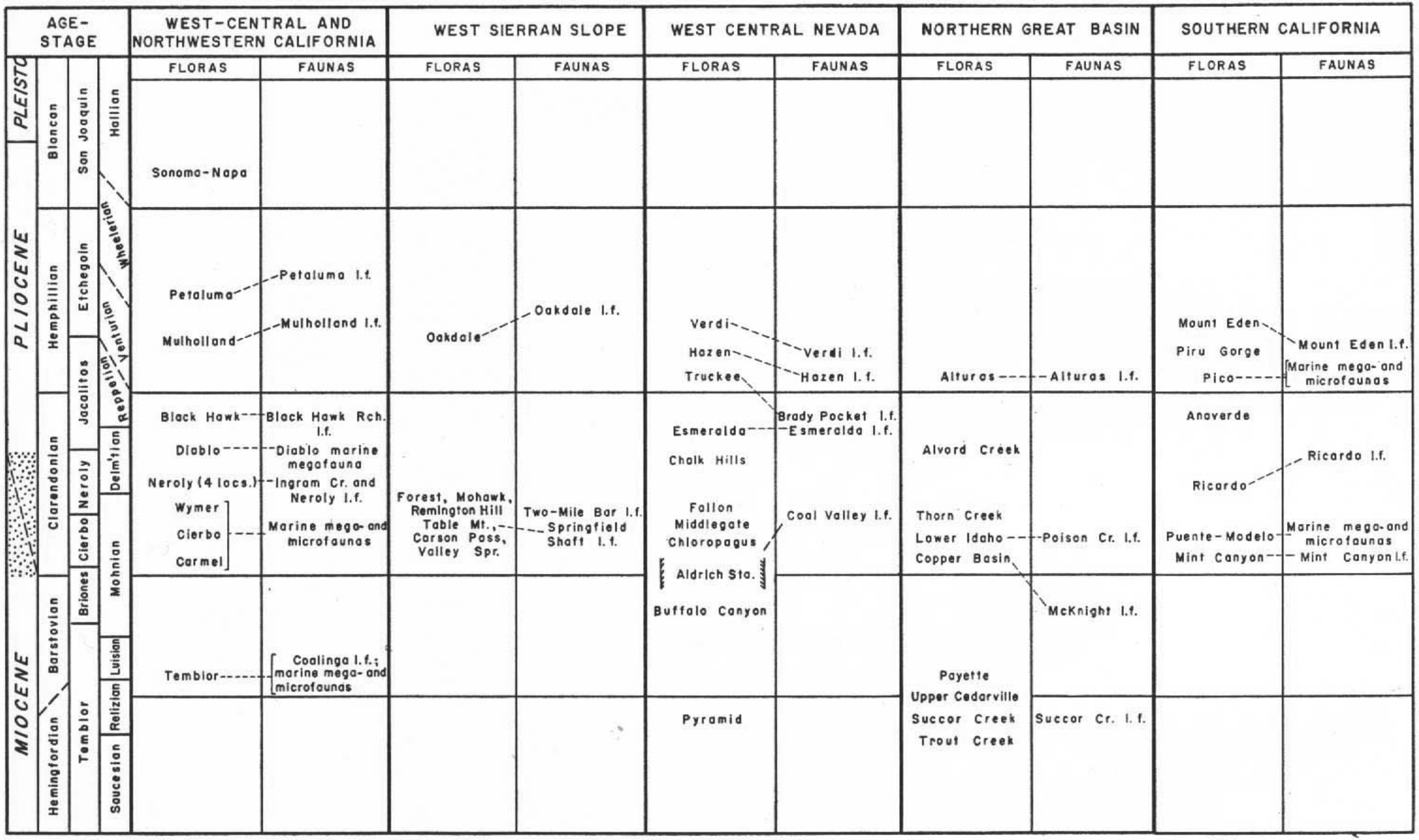


FIGURE 2.—RELATIVE AGES OF MIDDLE AND LATE TERTIARY FLORAS

Occurrence of marine and nonmarine faunas in the section is indicated in the right-hand column for each region; dashed lines show their stratigraphic positions relative to the floras.

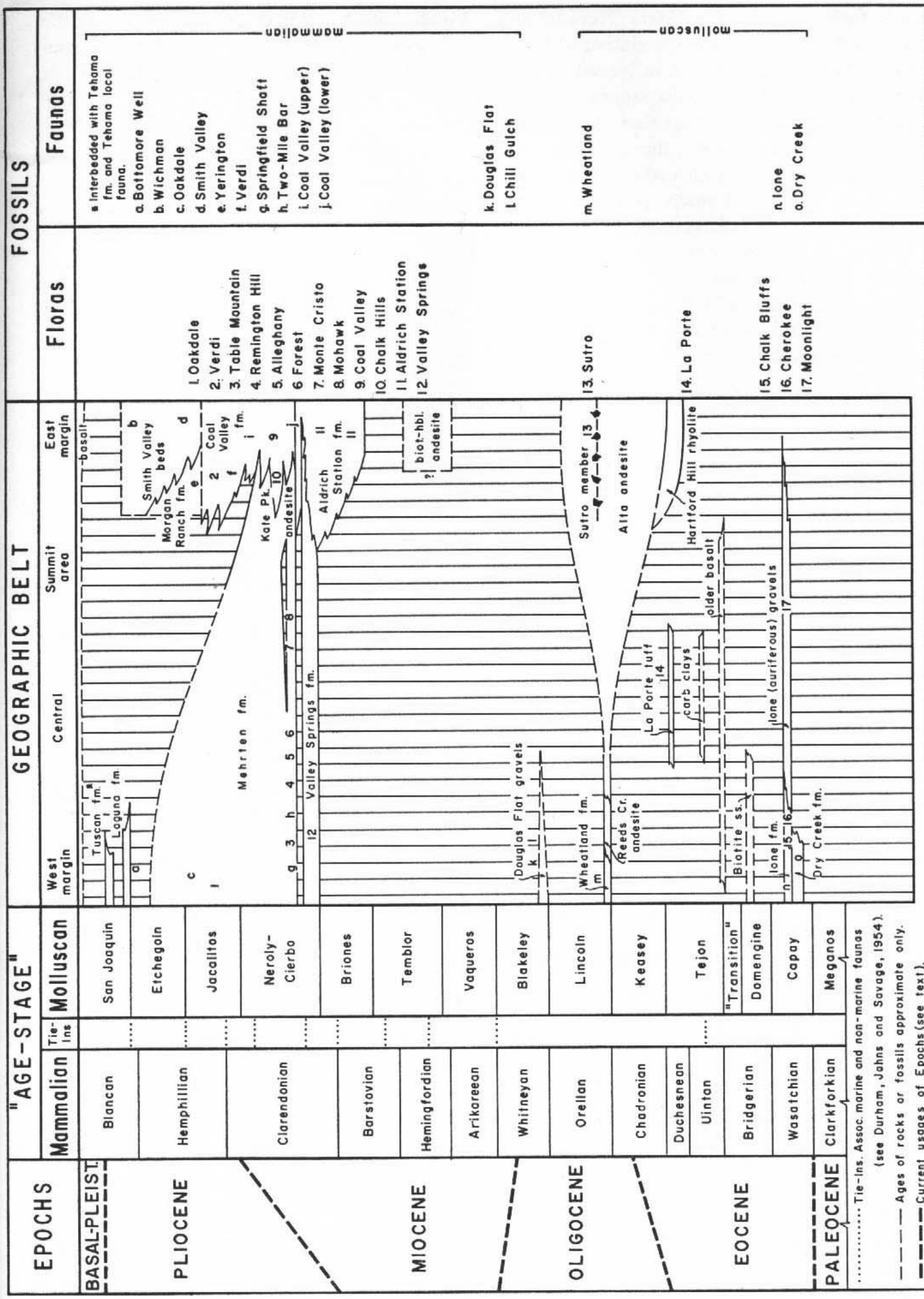


FIGURE 3.—TERTIARY STRATIGRAPHY OF THE CENTRAL AND NORTHERN SIERRA NEVADA

Peak formations in the Sierra Nevada and western Nevada, and the correlative andesitic sediments lying farther east in Nevada and to the west in coastal California represent a good lithic unit, and an important time unit.

In the Sierra Nevada the andesites and andesitic sediments which make up the Mehrten formation are at many points underlain by the Valley Springs formation, which includes as much as 500 feet of rhyolite tuff and associated fluvatile material. Although the contact may be disconformable there is no extensive time hiatus in this section because the Valley Springs flora is similar to that from the base of the overlying Mehrten formation (Axelrod, 1944, p. 219). The Valley Springs has a stratigraphic position no less significant than the base of the overlying Sierran andesites. Reconnaissance work in western Nevada demonstrates that rhyolites equivalent to the Valley Springs conformably underlie the lowest Kate Peak (Sierran) andesites at several localities. This includes the Coal Valley area where mammalian fossils of early Clarendonian age (U.C. Mus. Pal., locs. V3939, V4705, V4706) also occur just below the Kate Peak (Sierran) andesite. At this locality they are in the Aldrich Station formation which is a fluvio-lacustrine deposit of rhyolite tuff, pumice, diatomite, and siliceous shale containing the Aldrich Station flora (Axelrod, *in press*). To the north, at the western margin of the Carson Sink, rhyolite tuff beds apparently representing the Valley Springs formation lie conformably below the Kate Peak andesite and grade eastward into a thick lacustrine section dominated by siliceous shale which has yielded the Fallon flora of early Clarendonian age (Axelrod, *in press*). In the marine section of California the Valley Springs has its equivalent in the thick units of rhyolite tuff that are associated with the Cierbo formation in the Corral Hollow area (Huey, 1948) and southward (Anderson and Pack, 1915, p. 96–100), where it underlies the Neroly formation which is there charged with andesitic debris transported westward from the Sierra Nevada. Associated marine megafossils and microfossils indicate that these rhyolite tuffs are of Cierbo and Mohnian age, and a similar age is assigned to the Cierbo flora of the Corral Hollow area. Figure 4 illustrates in diagrammatic manner the east-west relations of the base of the Sierran andesite (Mehrten formation, Kate Peak andesite) and the underlying rhyolite (Valley Springs formation). It indicates that the Mio-Pliocene floras were living at a time of rhyolite activity, or immediately following it, during the inception of andesitic eruptions.

To interpret more fully the floras that lie along the transect from western Nevada to the Coast Ranges of west-central California, it is necessary to consider floras of similar age to the north and south because they provide data on regional environments which bear on the problem of altitude. That all these floras are of Mio-Pliocene age rests not only on evidence supplied by the plant fossils; in some areas the age is indicated by associated early Clarendonian mammals, and in other regions by molluscan or foraminiferal assemblages of Cierbo-Neroly and Mohnian-early Delmontian ages, respectively. (*See* Fig. 2.) Particularly critical is the fact that a number of these floras occur in sections that are also characterized by rhyolite tuff. Thus the Hog Creek and associated florules from the lower part of the Idaho (=Poison Creek) formation near Weiser, Idaho, occur in a section rich in rhyolite ash and pumice (Buwalda, 1923; Dorf, 1936). The Thorn Creek flora (Smith, 1941) from the region north of Boise, Idaho, is of similar age and occurs in a section containing pumice and rhyolite ash. The lower part of the Humboldt formation in northeastern Nevada, described by King (1878, p. 434–443), which is equivalent to the middle member of the Humboldt discussed by Sharp (1939), includes rhyolite tuffs associated with a fluvio-lacustrine section. The McKnight mammalian fauna from Bone Valley (King, 1878; Merriam, 1914), of late Barstovian age, apparently occurs low in this section. The ash-rich section of the middle Humboldt formation interfingers northward with a thick rhyolite section that centers near Jarbidge, where it contains the Copper Basin flora of late Barstovian or early Clarendonian age. These rhyolites apparently are equivalent to the Owyhee rhyolite of southwestern Idaho, which lies conformably on the Columbia Lavas and grades upward into the Idaho (= Poison Creek) formation. It would appear that the

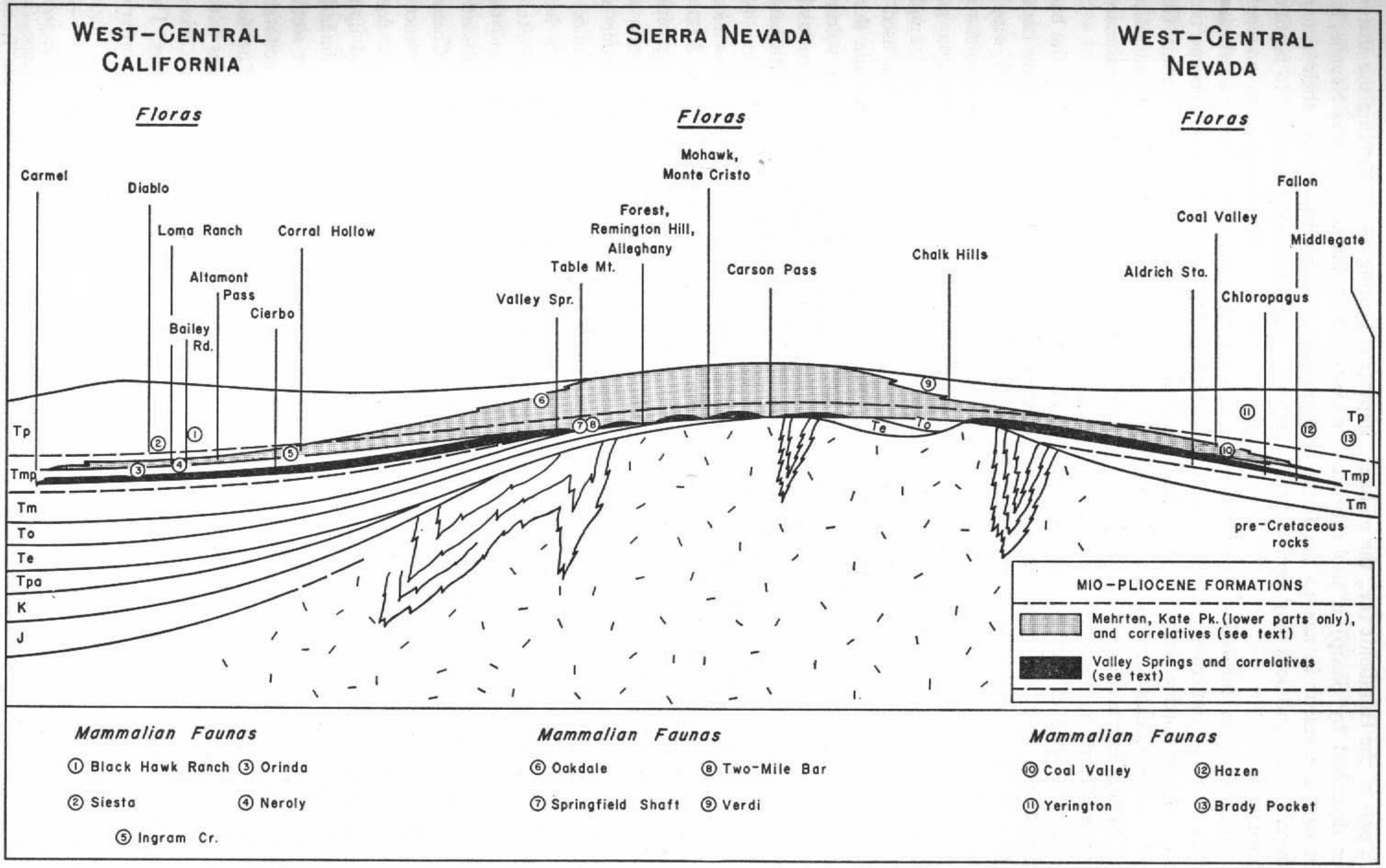


FIGURE 4.—STRATIGRAPHIC OCCURRENCE OF MIO-PLIOCENE FLORAS IN CENTRAL CALIFORNIA AND WESTERN NEVADA

ash-rich part of the Humboldt (*i.e.*, the middle member described by Sharp) is probably at least in part equivalent in age to the Idaho ( = Poison Creek), and both may represent the same formation.

The Mint Canyon formation of southern California contains numerous beds of rhyolite tuff in its middle portion where the flora and most of the mammals occur (Jahns, 1940; Axelrod, 1940b). Furthermore, the lower part of the near-by Ricardo has much rhyolite tuff and pumice at the level of the Petrified Forest (Webber, 1933), and the large mammalian fauna of mid-Clarendonian age comes from the overlying section (Merriam, 1919).

It is apparent that rhyolitic volcanics erupted over a wide area in the far West during Mio-Pliocene time and that much of this material was in the form of fine pyroclastics. In this connection it is significant that the diatomites which are so characteristic of the marine section of California also appear to have accumulated at this time when an abundant supply of silica from acid tuffs provided favorable conditions for the optimum development of these siliceous organisms (Bramlette, 1946). As shown by Bramlette, much of the diatomite has been altered to porcelaneous rocks, which, with the diatomite, make up a distinctive part of the Monterey formation. Since rhyolites were erupting contemporaneously in near-by regions eastward, they may have been one of the chief sources for the silica in these marine rocks. Thick sections of rhyolite which are slightly older than those discussed above are known also in the Great Basin and may have provided much of the silica for the earlier Monterey rocks of Luisian-Barstovian ages.

## Regional Environments

### *General Remarks*

If the Mio-Pliocene floras of the region are grouped according to similarity, they represent several provinces which differ widely in vegetation and, by inference, in climate. The areas occupied by these Mio-Pliocene environments include the vegetation of three major Tertiary Geofloras.[4] Since these environments have an important bearing on interpreting the altitude of western Nevada and the Sierra Nevada, it is appropriate to review briefly their general nature. Plate 1 has been prepared to facilitate discussion of these Mio-Pliocene environments. It shows the distribution pattern which is inferred to have existed in Mio-Pliocene time, not the actual occurrence of the Tertiary Geofloras. It expresses certain broad conclusions which may be drawn with respect to the areal relations of Mio-Pliocene vegetation.

This map has been constructed on the basis of the relatively few Mio-Pliocene floras known for the broad region shown (*see* Fig. 1), supplemented by inferences derived from somewhat younger and older floras, as well as from geologic and ecologic evidence. A few examples show how these inferences have been used to fill out the map. The western Nevada floras occur in sediments intercalated in volcanic sections typified by flows and pyroclastics ranging from rhyolite to andesite, with basalt also represented. To judge from modern volcanoes, such an occurrence for the floras makes the assumption of moderately high (3000 to 6000 feet) cones near the sites of deposition highly probable. The floras in this region are dominated by live oaks, and forest conifers are subordinate or rare. Comparative studies of modern and fossil plant accumulations have shown that only plants living at the site of deposition are among the dominants, and that those on bordering slopes are rare or absent in both the modern and ancient deposits (Chaney, 1925). In these Nevada floras the inference is that these rare conifers in the lowland floras were living chiefly on the middle and upper slopes of the bordering volcanoes. Similarly, thick boulder beds in the Thorn Creek section of south-central Idaho suggest that mountains bordered the basin of deposition. The fossil plants, preserved in lacustrine shales interbedded with the conglomerates and arkosic sandstones, contain numerous conifers. That they were more abundant on the bordering slopes where climate was cooler is highly

[4] The term Geoflora supplants the earlier term Flora in so far as it applies to the major units of Tertiary vegetation (Chaney and Axelrod, *in press*). For a more detailed discussion of the composition, time-space relations, and evolution of the Tertiary Geofloras, *see:* Chaney (1938a; 1938b; 1944a; 1948), Chaney and Hu (1940), Axelrod (1938; 1939; 1940a; 1950a; 1952).

probable. That a similar distribution prevailed elsewhere in the region wherever mountains were present seems likely in view of the known composition of the floras in the bordering region to northward.

Ecological inferences have been drawn also from the latitudinal and slope relationships of modern vegetation related to the fossil floras. Temperate vegetation grows at higher altitudes southward and at lower altitudes on cooler slopes facing east and north. A similar occurrence is inferred for the Nevada volcanoes and the Idaho hill country during Mio-Pliocene time. By contrast, semiarid vegetation extends northward today on warmer slopes facing south and west and at successively lower altitudes. Oak woodland and chaparral vegetation occupied the lower warmer slopes of central Nevada during Mio-Pliocene time but were replaced at higher levels, where climate was cooler and more moist, by temperate forests (Axelrod, 1940a; in press). Since woodland and chaparral also dominated the interior lowlands of southern California during Mio-Pliocene time, it is inferred that they occupied exposed sites in the intermediate region where no Mio-Pliocene floras are known. As another example, the subtropical Carmel and Puente floras of coastal California are very similar in composition. Although no Mio-Pliocene floras are known in the intermediate area, it is probable that similar vegetation occupied the mild seaward slopes of the coastal archipelago in the intervening region, By using inferences of this sort and depicting them on a schematic map, much can be shown that is purely speculative but is consistent with all the evidence available. Recalling that Plate 1 serves only to express a probable distribution pattern which supplies evidence for interpreting regional climate and topography, we may summarize briefly these Mio-Pliocene environments.

### *Arcto-Tertiary Geoflora*

The Arcto-Tertiary Geoflora was a summer-green temperate forest of deciduous hardwoods and conifers which occupied high northern latitudes during the early Tertiary and spread southward during the rest of the period as climate was cooling. In terms of present affinities, its species were similar to plants now living in three widely separated areas. Members of the West American Element have close counterparts in the conifer forests of western North America. The East American Element included plants similar to the deciduous hardwoods and conifers now found in eastern North America. Nearest relatives of species of the East Asian Element are in the temperate deciduous hardwood and conifer forests of northeastern Asia, a region which is floristically related to eastern North America. The regular association of species of all these elements at numerous localities during Tertiary time demonstrates the holarctic continuity of the Arcto-Tertiary Geoflora, both in time and in space. Yet it was not a homogeneous vegetational type during any part of that period. On the contrary, in each region it regularly displays a diversity of composition in response to local changes in relief and climate, and its successive changes in composition and distribution provide a sound basis for age determination (Chaney, 1936).

During Mio-Pliocene time the Arcto-Tertiary Geoflora was differentiated into three major provinces (Pl. 1). The first was a warm-temperate maritime province which occupied the outer coastal strip from the San Francisco Bay area northward into Washington. It included a number of warm-temperate relicts such as avocado (*Persea*), holly (*Ilex*), magnolia (*Magnolia*), palm (*Sabal*), and others which were surviving near the coast at this later date in a region of mild winter climate. Here they were living with such typical members of the Arcto-Tertiary Geoflora as alder (*Alnus*), birch (*Betula*), persimmon (*Diospyros*), sweetgum (*Liquidambar*), sycamore (*Platanus*), lingnut (*Pterocarya*), swamp cypress (*Taxodium*), and their regular associates. Judging from the requirements of modern species most similar to these fossil plants, rainfall in this coastal area was distributed rather evenly through the year, ranging from 35 to 40 inches at the south and increasing gradually northward along the coast. Summers presumably were warm and humid, and winters were mild, with rare frosts.

The second province was a temperate hill and valley region alternating with flood-plain and lake-border vegetation. It covered much of the Columbia Plateau and northern Great Basin and extended eastward to the Rocky Mountains. Deciduous hardwoods dominated it. Maple (*Acer*), alder (*Alnus*), birch (*Betula*), hornbeam (*Carpinus*), hickory (*Carya*), redbud (*Cercis*), beech (*Fagus*), sycamore (*Platanus*), poplar (*Populus*), oak (*Quercus*), and willow (*Salix*) were common, as were such conifers as water cypress (*Glyptostrobus*) and swamp cypress (*Taxodium*) which are now confined chiefly to lowland areas of high water tables. Fir (*Abies*), spruce (*Picea*), pine (*Pinus*), and other conifers were present but generally rare for they lived in bordering montane areas. Rainfall over the area probably ranged from 30 to 35 inches, distributed well throughout the year but possibly of biseasonal occurrence. Thus it is inferred that temperatures of this province were warm in summer and cool in winter and snows were common. This region graded southward to interfinger with the Madro-Tertiary Geoflora (Pl. 1).

The third province has montane characteristics. It was dominated chiefly by conifers of the West American Element, such as fir (*Abies*), spruce (*Picea*), pine (*Pinus*), Douglas fir (*Pseudotsuga*), coast redwood (*Sequoia*), and western red cedar (*Thuja*). Their common associates included species of maple (*Acer*), alder (*Alnus*), serviceberry (*Amelanchier*), birch (*Betula*), hornbeam (*Carpinus*), beech (*Fagus*), aspen (*Populus*), cottonwood (*Populus*), oak (*Quercus*), coralberry (*Symphoricarpos*), and elm (*Ulmus*), many of which represent cooler types, compared with species recorded in the more abundant floras of the lowlands. Judging from the requirements of related modern plants, rainfall in these upland areas was probably 35 to 40 inches, distributed more or less equally in summer and winter. Temperatures presumably were cool in summer, but the winters were cold, and snow probably fell regularly.

### *Madro-Tertiary Geoflora*

The Madro-Tertiary Geoflora, which apparently originated in the southwestern part of North America during the early Tertiary, migrated northward with expanding dry climate during the middle and later parts of the period. Madro-Tertiary species were chiefly drought-resistant or drought-deciduous, small- and thick-leafed plants similar to those now living in the semiarid sections of southwestern North America. The California Woodland and Chaparral elements included plants related to the oak and conifer woodland vegetation, and the dense chaparral communities of the summer-dry climate of California. The Sierra Madrean Element comprised woodland species similar to those now in the summer-wet region from Arizona to west-central Texas and southward into Mexico. The Southwestern Chaparral Element included a number of species similar to those living on the margins of woodland vegetation in Arizona, the Edwards Plateau, and Coahuila. The Sinaloan Element represented a drought-deciduous arid subtropical scrub (thorn forest) whose species resemble those now found on the moister warmer margins of the desert in eastern and western Mexico. The regular association of the species of these elements during most of the Tertiary attests to the unity of this geoflora in time and space. Its successive changes in composition and distribution, due chiefly to the trend toward drier climate during the period, provide a basis for age determination (Axelrod, 1938; 1939; 1948).

Plate 1 shows that two major provinces can be discerned in the area of distribution of the Madro-Tertiary Geoflora in Mio-Pliocene time. In the north its species were chiefly members of woodland and chaparral vegetation. Included in the woodland communities were madrone (*Arbutus*), buckthorn (*Bumelia*) cypress (*Cupressus*), ironwood (*Lyonothamnus*), avocado (*Persea*), digger pine and nut pine (*Pinus*), pistacio (*Pistacia*), sycamore (*Platanus*), cottonwood (*Populus*), live oak (*Quercus*), locust (*Robinia*), soapberry (*Sapindus*), laurel (*Umbellularia*), and Mexican chestnut (*Ungnadia*). Chaparral species were distributed in such genera as manzanita (*Arctostaphylos*), ceanothus (*Ceanothus*), mountain mahogany (*Cercocarpus*), bush poppy (*Dendromecon*), silk-tassel bush (*Garrya*), evergreen cherry (*Laurocerasus*), sumac (*Schmaltzia*), and scrub oak (*Quercus*). It is inferred that rainfall over the northern sector ranged from 20 to 25 inches and was distributed chiefly biseasonally. Temperatures probably were mild to moderately cool. In the more northern temperate areas, as in central to northern Nevada and on the flanks of the Sierra Nevada, the Madro-Tertiary Geoflora occupied exposed slopes and flats adjacent to cooler sites supporting the Arcto-Tertiary Geoflora (Pl. 1).

In the southern sector, woodland and chaparral vegetation were also characteristic in Mio-Pliocene time. But here they were associated with the arid subtropical Sinaloan Element, comprising such thorn-forest genera as acacia (*Acacia*), elephant tree (*Bursera*), paloverde (*Cercidium*), hopbush (*Dodonaea*), palm (*Erythea*, *Sabal*), kidneywood (*Eysenhardtia*), fig (*Ficus*), lead tree (*Leucanea*), and guamuchil (*Pithecolobium*). As judged from the requirements of related living species which are found regularly in the warmer frost-free sections of Mexico, milder winters probably typified this southern sector where precipitation over the lowlands was on the order of 15 to 20 inches, most of which fell in the warm season.

### *Neotropical-Tertiary Geoflora*

The Neotropical-Tertiary Geoflora included broad-leafed evergreen trees, shrubs, and lianes of living tropical families. Early in the Tertiary, under the influence of a warm mild climate with adequate rain, it ranged northward to Lat. 55° on the Pacific coast and extended far inland. Progressive chilling during the Tertiary is presumed to have restricted it gradually southward to tropical regions. It occupied a narrow coastal strip (Pl. 1) extending from Monterey through the coastal archipelago into southern California during Mio-Pliocene time, when it was dominated by arid subtropical types. Its recorded Mio-Pliocene species are in genera such as custard apple (*Anona*), sea grape (*Coccoloba*), fig (*Ficus*), magnolia (*Magnolia*), lancewood (*Nectandra*), avocado (*Persea*), palm (*Sabal*), and other subtropical types which mingled on bordering slopes with the pine-oak woodland and scrub communities of the Madro-Tertiary Geoflora. Ecological relationships of similar modern plants lead to the inference that rainfall over the coastal area south of San Francisco Bay was near 30 inches yearly, probably distributed chiefly as a summer maximum. Winters presumably were mild and frostless, but summers were probably hot and humid.

## Paleobotanical Evidence Regarding Altitude

### *Mio-Pliocene Floras in West-Central Nevada*

To evaluate the elevation of west-central Nevada we must remember that all the Mio-Pliocene floras in that area were relatively similar in floristic composition and represented a mixture of species derived from the Arcto-Tertiary and Madro-Tertiary geofloras (Pl. 1). Many of the 65 woody plants in the Aldrich Station, Chloropagus, Fallon, and Middlegate floras are related to species which dominate living communities on the lower western flanks of the Sierra Nevada, where yellow pine (*Pinus ponderosa*)—white fir (*Abies concolor*) forest adjoins woodland and chaparral communities (Axelrod, *in press*). This local diversity of ecologic conditions is well illustrated by the fact that Sierra redwood (*Sequoiadendron*) is in three of the four fossil floras and occurs today at the lower margins of the Sierran forest, as on the south fork of the Kaweah River, where it mingles with live-oak woodland and chaparral at an elevation of 3500 feet. The zone of overlap between forest and woodland in the present Sierra descends gradually to lower levels northward and at the latitude of the Nevada floras it is found commonly near 2000 to 2500 feet. This altitude therefore approximates that of the floras in west-central Nevada during Mio-Pliocene time. However, the Mio-Pliocene forest of west-central Nevada appears to have lived chiefly on cooler moister slopes a few hundred feet above the sites of deposition (Pl. 1), for forest species are represented by few specimens, compared with the predominant live oaks. Thus, it seems likely that if the average elevation over the lowlands in west-central Nevada during Mio-Pliocene time was greatly in excess of 2500 feet, a larger representation of forest species would be expected in these floras, in much the same way that forest becomes dominant at levels above 2500 feet on the windward slopes of the Sierra Nevada at this latitude today.

*East-West Comparisons of Vegetation*

Comparisons of the Mio-Pliocene floras of the Sierra Nevada with those in western Nevada show that the latter are most like the floras from the lower foothill belt of the Sierra Nevada, in a climatic as well as a floristic sense. The floras in both areas suggest an annual rainfall of approximately 25 to 30 inches, and in each region they are made up of an intermingling of plants derived from the Arcto-Tertiary and Madro-Tertiary Geofloras (Pl. 1). On the windward slopes of the Sierra Nevada a number of species such as hickory, tupelo, holly, elm, and sweetgum, find their nearest living relatives in the summer-wet sections of the northern continents. Members of these elements had a poorer representation over the lowlands of west-central Nevada at the same time. This suggests that summer rainfall was not only more frequent and in greater amount, but more effective on the coastward slopes where the evaporation rate presumably was lower. The coastward-slope floras also have avocado, magnolia, and other mild-winter types which are rare in the interior, indicating cooler winters in western Nevada compared with the windward Sierran slopes. Nonetheless, their relict occurrence in western Nevada at this time suggests that the region was still under the occasional influence of moderating oceanic climate. These sites may have been opposite low saddles in the range or near the heads of broad valleys up which mild air penetrated to the interior during winter. In any event, the moderate difference between the climate and vegetation on the lower windward flanks of the range and that to leeward in western Nevada must mean that the Nevada plateau was not at a very high elevation; otherwise the climate would have been cooler and the floras would have differed markedly. It is apparent also that the intervening ridge only comprised low hills; otherwise a drier climate would have occurred to the east and resulted in additional differences in vegetation.

Direct evidence of the elevation of the Nevada plateau is afforded by a comparison of the Remington Hill flora from the coastward slope (Condit, 1944a) with the Fallon flora east of the present range (Axelrod, in press). The Remington Hill flora contains coast redwood (*Sequoia*) and species of sycamore, cottonwood, oak (three species), poplar, willow, and madrone which are similar to those found with redwood today in the subhumid parts of its range in the hills north and south of San Francisco Bay. The Fallon flora has a number of plants related to those in the present Sierran forest, including yellow pine, white fir, nutmeg, Sierra redwood (*Sequoiadendron*), Oregon grape, madrone, willow, and cottonwood. Their small representation suggests that they lived on slopes a few hundred feet above the Fallon basin of deposition, which was dominated by live-oak woodland.

Apart from Sierra redwood, most of the typical members of the living Sierran forest occur also in the central Coast Ranges north and south of San Francisco Bay. In this region the lower margin of the Sierran forest is on slopes at elevations generally ranging from 1000 to 1500 feet above the redwood groves, in areas of cooler climate where snows are occasional in winter. The major difference between these environments represents approximately 5°F. in average January minimum temperature, which approximates the temperature contrast between the Remington Hill and Fallon floras from the coastward and leeward sides of the Sierra Nevada during Mio-Pliocene time. This estimate fits the paleoecology suggested by these floras. As judged from the Remington Hill and other near-by Mio-Pliocene floras (*see* Fig. 1), conifer forests of the Sierran type were not prominently developed on the coastward slopes of the Sierra Nevada at that time, which may have been too mild in winter for a forest of this type. But in the interior across the Sierran ridge, winter temperatures were sufficiently low in Mio-Pliocene time to support a Sierran conifer forest of the type commonly found at the margins of woodland and chaparral country. A difference in altitude of approximately 1500 feet between the Remington Hill and Fallon forests is sufficient to explain the temperature difference of 5°F., for the vertical temperature gradient in air averages 3½°F. for each 1000 feet elevation. Since the Fallon flora lived chiefly on slopes above the site of deposition, the difference in altitude between the Fallon and Remington Hill sites must have been less than 1500 feet and probably not much more than 1000 feet. This difference added to the 1000- to 1500-foot altitude which is here postulated for the Remington Hill site results in an estimate of from 2000 to 2500 feet for the lowlands about the Fallon basin of deposition.

TABLE 1.—MIO-PLIOCENE FLORAS FROM THE SIERRA NEVADA, THEIR PROBABLE ALTITUDE, AND THEIR YEARLY RAINFALL, AS INFERRED FROM RELATED LIVING VEGETATION*

| Fossil floras | Present position | Probable Mio-Pliocene altitude | Estimated rainfall (inches) |
|---|---|---|---|
| Carson Pass | on crest | near 2500 feet | 35–40 |
| Mohawk; Monte Cristo | middle-upper slopes | 2000 feet | 40–45 |
| Remington Hill; Forest | lower-middle slopes | 1000 1500 feet | 30–35 |
| Table Mountain | foothills | 500 feet | 25–30 |
| Valley Springs | low foothills to piedmont | 200–300 feet | 25–30 |

* Some of the data presented here for age, altitude, and rainfall differ moderately from those given in an earlier study of these floras (Chaney, Condit, and Axelrod, 1944).

### *Rainfall Gradient Across the Sierra Nevada*

Comparison of the rainfall gradient across the Sierra Nevada during Mio-Pliocene time with that on these slopes today provides an approximation of the relative change in slope and hence in the probable elevation of the range. Table 1 shows that the rainfall gradient on the Sierran slope was not very steep in Mio-Pliocene time. The floras in the lower piedmont near sea level suggest an annual rainfall near 25 to 30 inches which increased gradually to a maximum of from 40 to 45 inches on the middle-upper slopes and thence decreased to 25 inches over the lowlands of western Nevada. This is only a gentle gradient compared with that on these slopes today where rainfall in the Great Valley near sea level at this latitude averages 15 inches and increases to 70 or 80 inches in the wettest parts of the middle-upper slopes, with a decrease at higher levels and a continued decrease to the lee of the range in the Nevada desert, where it is less than 5 inches.

In evaluating these rainfall gradients to arrive at an estimate of altitude, the wettest part of the middle-upper slope is the most sensitive indicator of elevation, for precipitation increases steadily to a maximum at this level and thence decreases. Compared on this basis, the present gradient shows an increase of approximately 60 inches compared with 20 inches for Mio-Pliocene time, which suggests a Mio-Pliocene gradient only a third of the present one. This leads to the inference that the humid middle-upper slopes lay near 2000 feet in Mio-Pliocene time and, as an average, the general summit region was not much more than 1000 feet higher.

### *Carson Pass Flora*

The estimated altitude of the summit area in Mio-Pliocene time is strongly supported by the Carson Pass flora which is on the present crest and lay near the Mio-Pliocene divide. The flora has been collected recently from three localities within 50 feet of the base of the andesite section which rests on a granitic surface of low relief. The flora is chiefly a riparian assemblage of maple (*Acer*), tupelo (*Nyssa*), sycamore (*Platanus*), avocado (*Persea*), poplar (*Populus*), lingnut (*Pterocarya*), and willow (*Salix*). It provides a remarkable contrast to that at the fossil locality today, which is at an elevation of 9100 feet in the arctic-alpine zone of meadowland and fell-fields above the subalpine forest of mountain hemlock and whitebark pine. This flora probably was laid down at not more than 2500 feet and probably was lower. This estimate agrees with the upper limits of sycamore today on the lower western flanks of the range at this latitude, and its fossil relative was one of the dominants of the flora. The absence of conifers in the flora also points to a relatively low altitude. If it had lived much above 2500 feet conifers might have been expected in at least moderate numbers, for they

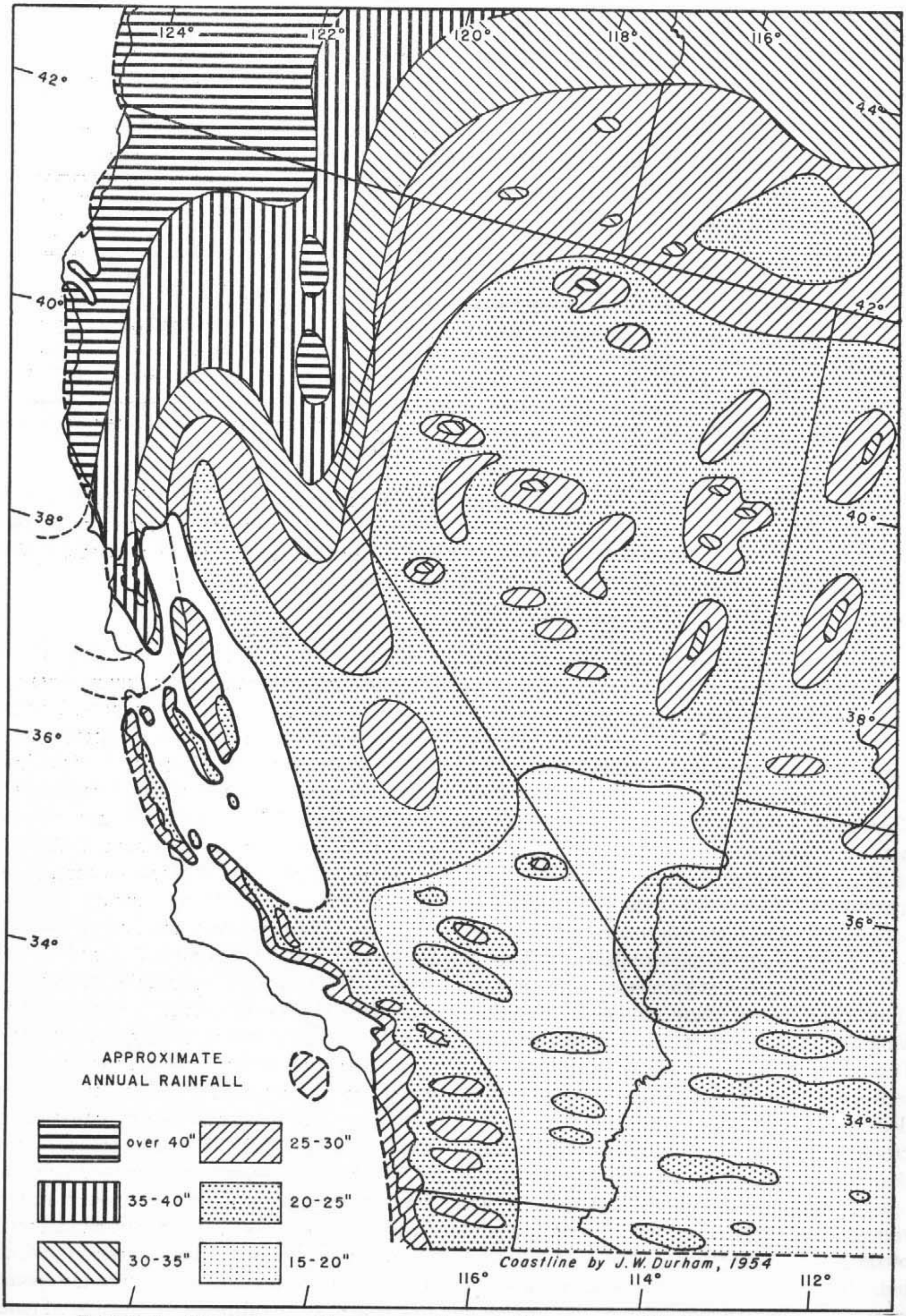


FIGURE 5.—DISTRIBUTION PATTERN OF ANNUAL RAINFALL IN MIO-PLIOCENE TIME
Inferred from data in Plate 1

constitute an important part of all the Nevada floras not far to the east where they blanketed the slopes above the basin of deposition (Pl. 1).

*Mio-Pliocene Rainfall*

Figure 5, which shows the presumed regional distribution of annual rainfall in Mio-Pliocene time, was drawn on the basis of the rainfall requirements of living vegetation most similar to the Mio-Pliocene floras. It outlines the relation of the Sierran province to west-central Nevada and to the bordering environments at the north and south. In filling out this map for areas where Mio-Pliocene floras are not now known, data from slightly older and younger floras of the region have been used (Fig. 1; Pl. 1). The evidence, although not detailed,[5] indicates that the whole Sierran province was a relatively minor topographic feature at this time. The climatic differences recorded by these contemporaneous Mio-Pliocene floras on both sides of the present Sierra Nevada can be accounted for by assuming that, as an average, the range rose no more than 1000 feet above the Nevada plateau. Judging from the climatic effects of similar low ridges on related vegetation today, it is concluded that if the Sierran summit was much more than 2000 feet above the Nevada lowlands in Mio-Pliocene time, a climate would have existed to leeward which was drier and cooler than that recorded by the Mio-Pliocene floras.

*Discussion*

These data lead to the inference that in its broadest features the average summit level of the central and northern portion of the Sierran block lay near 3000 feet. In general the late Tertiary volcanics rest on a topography of varied yet generally low relief. In the foothill belt the volcanics were laid down on a gently undulating plain with wide valleys separated by low broad interfluves; locally in this belt old monadnocks of basement rock apparently rose above the general level. In the central strip, the late Tertiary volcanics accumulated on a surface of moderate relief characterized by wide valleys separated by broad rounded ridges rising from 500 to 1000 feet above the valleys. The summit region was slightly more rugged, with the higher hills rising generally from 1000 to 1500 feet above the 2- to 4-mile wide valleys in the passes leading east.[6] In local sections, as in Pyramid Peak range west of Lake Tahoe, a few high hills of basement are believed to have lain sufficiently above the general summit level so that they were not covered by a thick volcanic cover (Lindgren, 1911, p. 37–39). It seems more probable that a somewhat thinner andesite section accumulated there and has since been eroded, possibly because of greater uplift in this local region. A thin cap of Kate Peak andesite occurs a few miles east of the Pyramid Peak range, at a higher altitude. It is on the peak 1 mile southwest of Jobs Peak (Markleeville quadrangle) at an elevation of 10,400 feet, whereas Pyramid Peak is only 10,020 (Carniss Curtis, personal communication, October 1955).

There is some evidence that the range gradually decreased in altitude northward in Mio-Pliocene time, in much the same way that the Sierran block today falls off to lower levels northward where it disappears under the volcanic cover of Mount Lassen. A newly discovered small Mio-Pliocene flora near Juniper Valley (Fig. 1, loc. 19), which lies east of the north end of the Sierra Nevada, appears to be more humid than floras of comparable age in west-central Nevada. If its age is determined correctly, and if larger collections substantiate the general ecologic implications, the barrier at the west was quite low or essentially nonexistent at that time. Thus the summit line of the Sierran block may have decreased northward from the Carson Pass area. In this distance of 100 miles the ridge probably descended to an average level of near 2000 feet at Donner Pass, with an additional drop of 500 to possibly 1000 feet in the next 50 miles to the Lassen area.

Judging from the common occurrence of foreign clasts in the pebble conglomerates in the

[5] Many climatologists have drawn rainfall maps from weather stations that are as scattered geographically as the "stations" recorded here, with results that are as generalized as those reached here.

[6] The author is indebted to Frank S. Hudson who made available a map of the north-central Sierra Nevada, covering parts of the Ione, Placerbille, Colfax, and Truckee quadrangles, which contours the base of the andesite and illustrates the nature of the prevolcanic surface.

basal parts of the andesite section, it is evident that drainage must have been westward across the Sierran ridge (Pl. 1). Paleoecologic data suggest that these seaward-draining valleys probably had elevations not greatly in excess of about 2000 to 2500 feet in the divide area. The floras in the basal part of the volcanic section sediments, such as siliceous shale well-bedded regularly are preserved in lenticular lacustrine water-laid tuffs, and tuffaceous siltstone, which are associated with fluviatile deposits. These relations suggest that small ponds and oxbow lakes occupied the meandering parts of the river valleys which incised the low Sierran ridge.

## Paleogeographic Implications

### *General Statement*

The paleoecologic and paleoclimatic data reviewed above for the Mio-Pliocene floras of the Sierra Nevada and west-central Nevada, supplemented by data from floras of similar age in bordering regions to the north and south, appear to complement and reinforce one another with respect to the average altitude of these major topographic features during Mio-Pliocene time. Although the inferred elevations are approximations only, it seems probable that they are within 500 feet of average levels. Since the suggested altitudes have important implications to geologic, climatic, and biologic problems, it is desirable to outline their nature briefly.

### *Geologic*

The preceding estimates of elevation appear to agree with known geologic facts. Figure 6 compares the topographic profile across the region today with that inferred for the interval just before the outbreak of Mio-Pliocene vulcanism in the Sierra Nevada; the volcanoes shown in Nevada are slightly older (*i. e.*, upper Miocene). The profiles were drawn from sea level in the Valley of California through the Lake Tahoe area to the margin of the Carson Sink in western Nevada, a distance of 140 miles. The vertical scale was exaggerated twice to show the topography clearly.

Following vulcanism, diastrophism resulted in major vertical displacement of the range during late Pliocene and early Pleistocene times, and uplift increased southward. The granodiorite-volcanic contact now lies at 7300 feet in the Donner Pass area, but at Carson Pass 50 miles southward the contact is at 9000 feet. Taking 2000 and 2500 feet as the average elevations for the Mio-Pliocene valleys in the Donner and Carson areas at the outbreak of vulcanism, uplift in the Donner area was approximately 5300 feet, compared with 6500 feet at Carson Pass. This increased elevation of the range was caused by at least three factors. In some measure—possibly small and local in extent—it was due to gentle folding (Hudson, 1948; 1951). A good part of it was due to large-scale faulting, which is now expressed as a series of giant treads (basins) and risers (ranges) which, in general, fall off progressively to the east of the main scarp, with the basement lying near sea level in the deeper basins of west-central Nevada (Axelrod, *in press*). The amount of absolute uplift by faulting is difficult to estimate because differential movement on the blocks lying to the east of the crest complicates the picture, as does reverse faulting. The large marginal faults which bound the east-facing scarps of the Sierran block suggest an average maximum figure of approximately 3500 feet for the displacement of the volcanic-basement contact in this section of the range. General regional uplift was also an important element adding to the height of the range following the volcanic episode, as suggested by LeConte (1889) and discussed by Lindgren (1911) and Hudson (1955). It is difficult to estimate the increase in elevation by regional uplift alone, yet if 3500 feet is used as an average maximum uplift that may have been caused by faulting, the remainder may represent the minimum elevation due to regional uplift (Table 2). These figures suggest a gradually southward-rising warp which accounted for a 1200-foot rise of the summit area from Donner Pass southward to the Carson Pass region 50 miles distant in the post-volcanic interval.

To the east, the lowlands of west-central Nevada now lie fully 1500 to 2000 feet above the presumed Mio-Pliocene average level. This increased elevation of the lowlands was caused

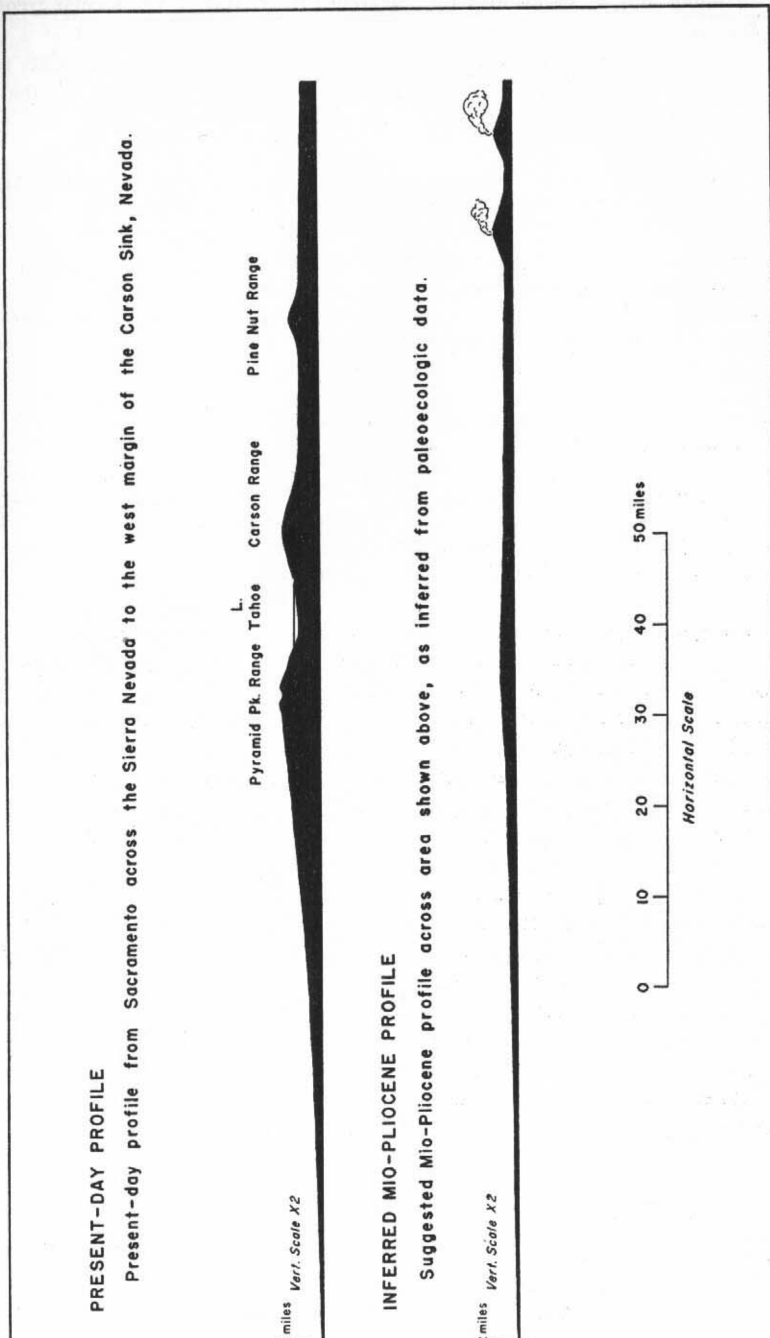


FIGURE 6—TOPOGRAPHIC PROFILE ACROSS THE CENTRAL SIERRA NEVADA TODAY COMPARED WITH INFERRED PROFILE JUST BEFORE MIO-PLIOCENE VULCANISM

in part by basin filling and probably also by regional uplift, for the floors of these basins now lie near sea level (Axelrod, *in press*). All the basins in western Nevada did not originate by faulting, as Nolan (1943, p. 182–184) has implied. In the Middlegate region the sediments clearly lie on an old volcanic terrain, and the basin probably originated by local downwarping. On the northern and southern margins of the Carson Sink, Miocene and younger rocks rest everywhere on pre-Tertiary basement rocks. Both damming by lavas and downwarping may have occurred in basin development here. In the Coal Valley area west of Walker Lake relatively fine upper Miocene sediments lie on crystalline rocks on the east side of the basin, whereas to the west the overlying lower and middle Pliocene section is buttressed against an old scarp. It is apparent that the only generalization that can now be made is that different basins in western Nevada have had different histories, and that each one must be worked out separately.

TABLE 2.—ESTIMATE OF REGIONAL UPLIFT IN THE NORTH-CENTRAL SIERRAN SUMMIT AREA*

| | Donner Pass | Carson Pass |
|---|---|---|
| 1. Present altitude of basement-volcanic contact on Sierran summit in Mio-Pliocene valleys | 7300 feet | 9000 |
| 2. Inferred Mio-Pliocene altitude of basement-volcanic contact of above features | 2000 | 2500 |
| 3. Amount of increased elevation due to diastrophism (1 minus 2) | 5300 | 6500 |
| 4. Approximate maximum by faulting | 3500 | 3500 |
| 5. Approximate minimum by regional uplift (3 minus 4) | 1800 feet | 3000 feet |

* The summit region probably had from 1000 to 1500 feet of relief. The figures in 1 and 2 above represent the elevations of the seaward-draining valleys in the summit area.

### *Climatic*

*Factors.*—Post - Mio - Pliocene climatic changes in the Far West appear to have been due in part to a secular climatic trend during the Tertiary, and in part to the building up of topographic barriers by vulcanism and diastrophism. Since both were effective concurrently, it is difficult to estimate their relative importance at any one time. The following sketches the nature of the secular trend which culminated in the development of a mediterranean climate and also the probable role that increased relief had on modifying the climate of the region.

*Secular effects.*—The major climatic trend of the Tertiary involved the chilling of the oceans and the development of drier land areas characterized by higher summer and lower winter temperatures. The broad zonal climates of the early Tertiary developed into the narrow zonal or cellular patterns of today. That the oceans chilled progressively during the Tertiary is evident from the ecological relations of fossil and modern shallow-water marine invertebrates throughout the world. Recent detailed paleoecological studies of the Tertiary faunas of the Pacific coast (Durham, 1950) lead to the inference that at this latitude (40° N.) there was a shift in minimum winter shallow-water temperatures from 25° C. (77° F.) in the Eocene to 11.5° C. (52° F.) at the end of the Tertiary, and the data suggest only a gradual change. The Tertiary Geofloras reflect an increase in the severity of continental climates during the same interval. Most of the dominant subtropical forests representing the Neotropical-Tertiary Geoflora were replaced over middle latitudes by middle Tertiary time by the temperate Arcto-Tertiary Geoflora, except for a narrow coastal strip where tropical relicts are recorded. Woodland, chaparral, and grassland vegetation of the Madro-Tertiary Geoflora expanded widely over the lowlands of the Far

West in the late Tertiary, displacing much of the Arcto-Tertiary Geoflora in its southern sector. Sage and then desert communities dominated the lowlands of this region at the end of the period. Thus the Tertiary Geofloras record a shift from equable climates of ample rain and mild winters to extreme continental climates of low rainfall and wide ranges and extremes of temperature at the end of the period.

As discussed by MacGinitie (1937; 1941), this secular trend toward cooling oceans and more extreme land climates gradually brought into existence a permanent north Pacific high-pressure system during the summer season, particularly following Miocene time. Winds moving from the north Pacific high over the colder ocean would take up relatively less moisture compared with the earlier Tertiary. But more important, the winds blowing onto the land area were being warmed and becoming drier and had lower potentialities for rain in the warm season. By contrast, in the middle and early Tertiary a warm ocean provided moist warm air which rose gradually as it crossed the continent, producing convectional showers during the summer season when the temperature contrast between the ocean and the land was much less pronounced. The temperature gradient between the Eocene tropics which extended to Lat. 55° N. and the cool temperate regions at latitudes above 70° was much less than it is today. The polar front must have been greatly weakened and restricted far to the north in Eocene time, with rare winter cyclonic storms entering middle latitudes where the chief precipitation was of the tropical convectional type in summer time. During middle Tertiary time, with the northern margin of the tropics near Lat. 40° N., conditions essentially transitional to those of the present day may have prevailed. The frequency of winter storms was now probably increased at middle latitudes, with possibly a third to a half of the yearly precipitation falling in the winter season. The decrease in summer rain following Miocene time was particularly marked, as indicated by the successively younger floras in the far West which contain progressively fewer species whose modern correlatives require summer rain. This relationship probably correlates with the continued trend toward chilling oceans and the development of hotter land areas in the summer season, with the resultant reduction in summer rain. To judge from the evidence supplied by the Tertiary marine isotherms (Durham, 1950), the driest continental climate would have occurred in mid-Pliocene time, a conclusion reached earlier on the basis of plant evidence (Axelrod, 1948). It was also during this stage that most of the fossil plants that are indicators of summer rain show a great reduction in numbers, and only a few remained in the coastal region into the Plio-Pleistocene interval. Thus by the end of the Tertiary the secular climatic trend had led to the development of a new climate on the west coast—a mediterranean climate of dry summers and wet winters with precipitation of cyclonic origin chiefly.

*Topographic effects.*—Vulcanism and diastrophism in late Cenozoic time probably account in large measure for the extreme climates which now prevail over the lowlands of Nevada and on the summits of the Sierra Nevada and the higher basin ranges. There can be no doubt that the secular climatic trend of the Tertiary shifted rainfall distribution from a dominant summer occurrence of convectional showers to a maximum of winter precipitation of cyclonic origin and resulted also in a general lowering of precipitation on the west coast. But it cannot account for the present desert area of Nevada which has only 4 inches of rain. Under present climatic conditions, and with low hills at the site of the Sierra Nevada and the Cascades to northward, the present desert region probably would be sufficiently moist to support a piñon-juniper woodland.

Comparisons of the Mio-Pliocene floras of west-central Nevada with floras of middle Pliocene age in the same region show a change from woodland and forest living under 25 to 30 inches rainfall, to semiarid savanna, grassland, and stream-border vegetation persisting under 15 inches precipitation (Axelrod, 1948; 1950c). This diminished rainfall might be ascribed to the effects of vulcanism which had added approximately 3000 feet of andesite to the Sierran ridge by the close of early Pliocene time. If such a topographic factor were in operation, the floras to the lee of the range should reflect a greater reduction than those of the same age on the windward slopes of the range or in west-central California (Axelrod, 1944). Since the floras in the three areas indicate approximately the same decrease in precipitation from Mio-Pliocene into middle Pliocene time, vulcanism could not have materially increased the height of the range. This probably was because the crust could not support the volcanics on the Sierra Nevada and adjacent Nevada. To maintain isostatic balance, the basement would have to sink and displace a mass of sima equal to the added volcanics. Since an andesite blanket 3000 feet thick would have to subside approximately four-fifths to come into equilibrium, the surface would be only about 500 feet higher than before vulcanism. This appears to be of the right order of magnitude for the average maximum thickness of the volcanics, for a thicker section would have resulted in a higher ridge, and hence the rain-shadow effect would have been pronounced.[7] Thus the summit of the range may have been at approximately 3500 feet in the middle Pliocene, compared with the 3000 feet inferred for the interval preceding Mio-Pliocene vulcanism. The data suggest, therefore, that the decrease in rainfall recorded by the middle Pliocene floras was due chiefly to secular change and not to a pronounced topographic effect. It was only in post-middle Pliocene time, largely in the late Pliocene to middle Pleistocene interval, that warping and faulting increased the altitude of the Sierran crest line from 5000 to 6000 feet in this north-central section. The effects of warping and faulting increased southward, and 100 to 150 miles away maximum uplift was approximately 7500–9000 feet. This would clearly have accounted for a 10- to 15-inch reduction in precipitation over the Nevada basins, so that widespread desert environment came into existence (Axelrod, 1950c).

The arctic-alpine and subalpine zones now in the summit region of the Sierra Nevada and the higher basin ranges are thus due primarily to a topographic factor alone, and not to a long-term climatic trend. Increasing the height of the Sierran summit 6000 to 8000 feet by vulcanism and diastrophism in late Cenozoic time would have lowered the January temperature from 20° to 28° F. below that which prevailed on the Mio-Pliocene crest. The higher summits had thus attained sufficient height so that snow and ice could persist through the summer. By increasing the altitude of the Nevada lowlands 2000 feet in late Cenozoic time the average January temperature would have decreased approximately 7° F. If this figure is added to the 5° F. difference between the lower Sierran slopes and western Nevada which is postulated for Mio-Pliocene time, the total of 12° F. agrees closely with the present difference in average January temperature between these regions today and hence tends to support the earlier conclusion.

[7] Assuming a thickness of 3000 to 3500 feet (average 3250 feet), the surface would be increased approximately 700 feet; with a load of from 4500 to 5000 feet (average 4750 feet) the surface would rise approximately 1000 feet.

*Biologic*

These climatic and topographic changes over the Sierra Nevada and west-central Nevada during the later Tertiary opened new ecologic zones for plants and animals. Among the new sites in the uplands of both regions were montane summits characterized by (a) arctic-alpine meadows and fell-fields, (b) a zone of subalpine forest, and, in addition, in the Sierra Nevada, (c) a moist-cold zone of fir forest. Over the lowlands, successively drier and more extreme environments came into existence, as is recorded by the gradual displacement of woodland and forest by steppe (sage, grass) and desert vegetation (Axelrod, 1950c).

The advent of a mediterranean climate at the close of the Pliocene had an important effect on plants in these new zones, as well as in the older forest, woodland, chaparral, and grassland communities bordering them. Many types which had lived under summer rain were eliminated as effective summer showers disappeared, and communities were opened for types tolerant of dry summers in environments ranging from the humid west slope of the Sierra Nevada across the new subalpine tract and into the desert at the east. In herbaceous groups particularly, hybridization and other genetic changes may have given rise to many new types which could, at least marginally at the outset, invade these new zones in a novel climate. Microgeographic isolation in these areas of abrupt and diverse changes in climate and relief would permit the existence of divergent adaptive types in proximity. Further hybridization would favor the development and spread of types more strongly adapted to the extreme environments. Fluctuating glacial and pluvial climates probably intensified the amount of hybridization, for rapid climatic fluctuations—such as four glacial advances and retreats in the Wisconsin—must have continually altered the spatial relations of populations. Continued crossing of divergent, but rather freely recombining, genotypes would establish new variants even more narrowly adapted to these extreme rapidly fluctuating environments. In this way scores of highly adapted types may have arisen quickly, compared with rates of evolution in related groups occupying more uniform areas.

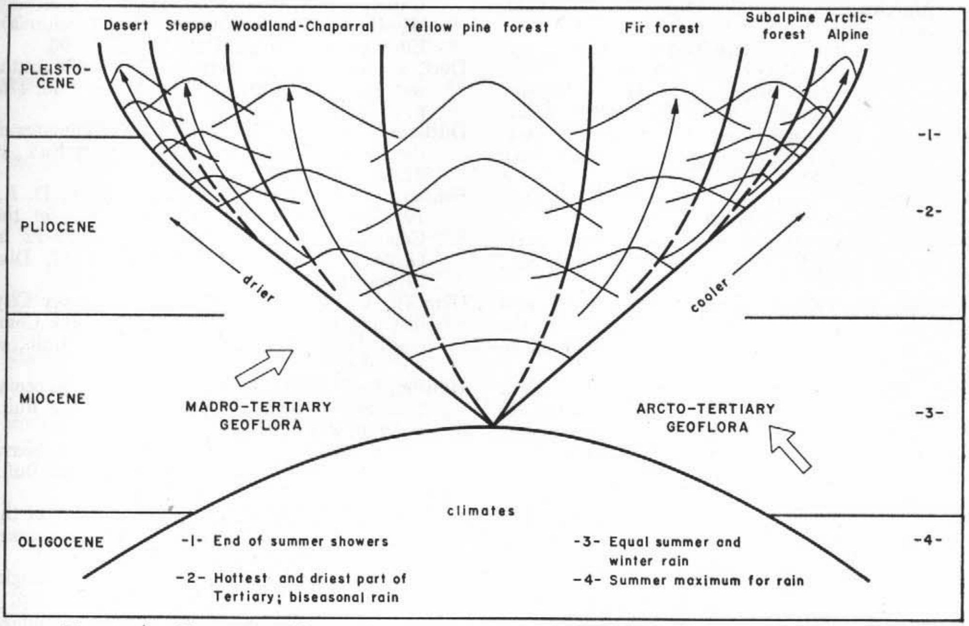


Figure 7.—Expanding Zonal Relations in the Region during the Later Cenozoic

Figure 7 summarizes the shifting relations of the major adaptive plant zones in this region during the later Cenozoic; they might also be termed subzones of a montane zone. The invasion of a new zone by a group of organisms clearly represents a basic evolutionary event which involves secular change of the zone in a physical as well as a biological sense (Simpson, 1953, Chap. 7). As suggested by Simpson's discussion, the broader zones express a more generalized adaptive type, whereas the narrower ones (desert and arctic-alpine) are more specialized. The modal curves shown in the figure suggest the direction and intensity of selection, with the asymmetry implying a linear component imposed by shifting climatic factors in time. Although the actual picture was far more complex than can be shown (Fig. 7), the over-all pattern nonetheless clearly suggests the expanding opportunities for life in this region during the later Cenozoic.

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