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CENOZOIC CLIMATE AND THE ARID SOUTHWEST

By

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ABSTRACT

The paleobotanical record in the Southwest is scant and most of the paleoclimate must be inferred from surrounding areas. This approach is defensible because the climate of Arizona and New Mexico has its source in the oceans outside the surrounding areas, and the climate of the Southwest can be inferred from the modifying effects of the intervening areas.

The Cenozoic climate in the Southwest has been affected regionally by a general lowering of temperature from Eocene to Pleistocene time and locally by mountain building that disturbed atmospheric circulation. The time and degree of elevation of western mountains and the stage of the secular temperature trend provide the clue to interpretations of Tertiary climate in the Southwest.

In early Tertiary time, convectional moisture from the Gulf of Mexico brought heavy rainfall and warm temperatures into the Southwest. By middle Tertiary time, the trend to cool temperatures had begun and the rising Sierra Nevada in middle Miocene time created a rain shadow over the Southwest. By middle Pliocene time, the Cascade Mountains and Coast Ranges were also interfering with the circulation pattern from the Pacific Ocean. In spite of the increased strength of the cyclonic circulation cell due to the cooling trend of the Tertiary, the Southwest had taken on an arid character similar to that of today.

Near the end of Miocene time the Colorado Plateau was elevated to a height where cooler temperatures prevailed. Now a dry, subtropical climate exists only in the low southwestern parts of Arizona and the Sonoran desert.

The Pacific cyclonic cell, which had intensified and shifted by late Pliocene time and brought moisture to upland areas, may have had its culmination in the development of the interior lakes of the Pleistocene.

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Roger Y. Anderson[1]

INTRODUCTION

This paper presents a brief discussion of the climate and the climatic changes that occurred during Tertiary time in the arid southwestern portion of the United States. A discussion of Pleistocene climate has been omitted, but some new information about the climatic changes that immediately preceded the first glacial stage is evaluated in terms of Pleistocene and modern climate.

Paleobotany has proved to be the most sensitive and suitable tool for the interpretation of climate because of the narrow climatic tolerance of many genera and species of plants. The best climatic evidence has been obtained from studies of plant megafossils, usually leaves, and plant microfossils. Plant megafossils are excellent indicators of various conditions of temperature and moisture because of their accuracy of identification with living plants whose ecology is known. They have a disadvantage in that they tend to represent mostly the lowland site of deposition and do not tell us about the upland flora or climate. Pollen and spores, however, reach the sites of deposition from the uplands and the lowlands and give a more accurate total picture of the climate, but with the distinct disadvantage of less definite identification with extant genera and species.

The paleobotanical record in the arid Southwest is scant and most of the paleoclimate must be inferred by studying the results obtained from surrounding areas such as California, Oregon, Nevada, Colorado, and Oklahoma. At first this approach would seem to present serious difficulties, but the climate of such places as Arizona and New Mexico has its source in the oceans outside the surrounding areas and it is possible to infer the climate in the arid Southwest by studying the modifying effects caused by the intervening areas.

It is beyond the scope of this paper to present detailed botanical evidence, and only the general results of the studies of several investigators in terms of temperature and moisture will be considered. Information about the occurrence and ecologic significance of several genera obtained from my own studies will be discussed more thoroughly. The geographic locations of fossil flora mentioned in the paper are noted on an index map (fig. 2.1).

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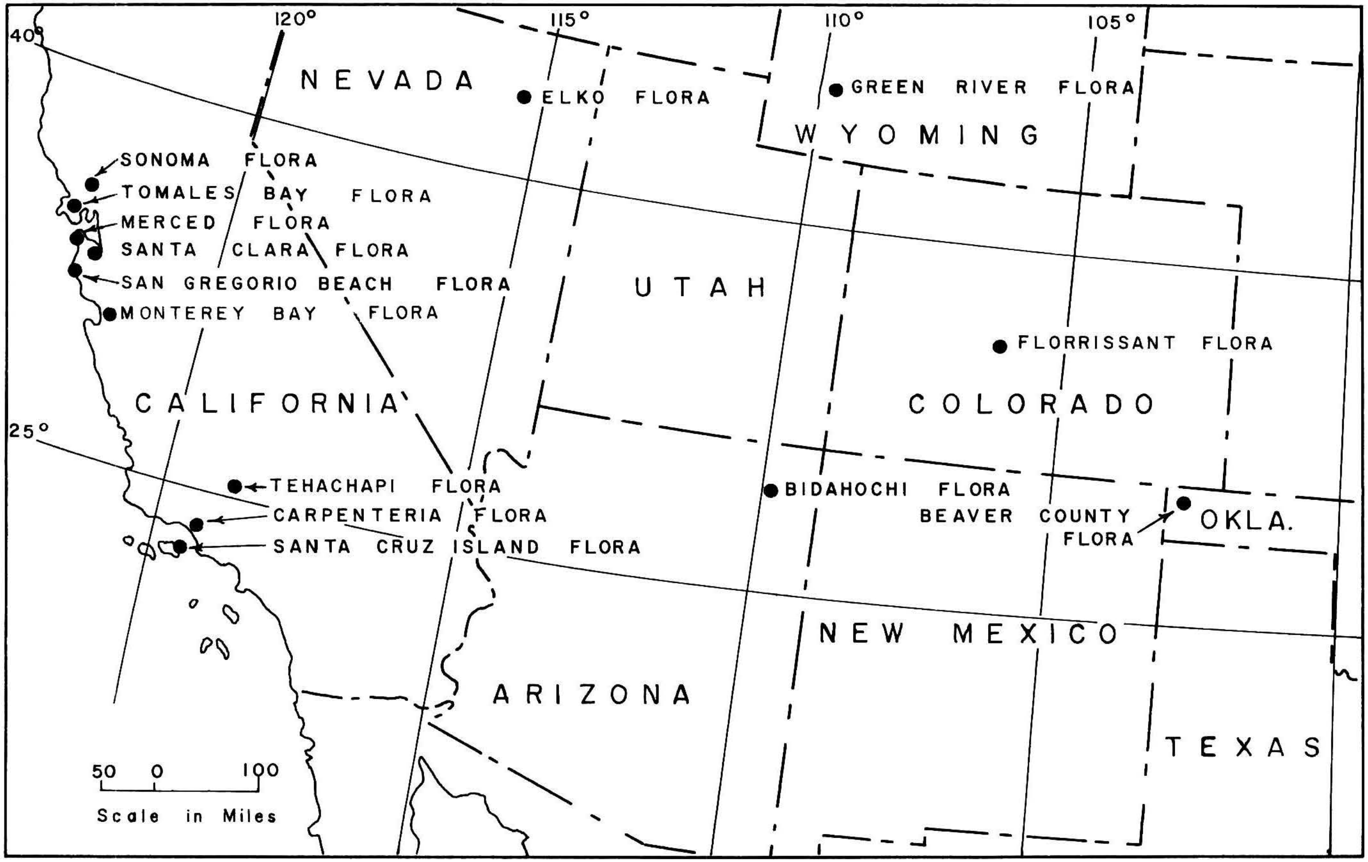

Figure 2.1.--Map showing location of fossil flora.

BROAD ASPECTS OF TERTIARY CLIMATE

The broad aspects of the climatic changes that occurred during the Cenozoic Era in the arid Southwest can be understood by reviewing two phenomena whose climatic effects are closely interrelated. The first has been deduced from the fossil history of a variety of animals and plants and is a gradual lowering of temperature from Eocene time to the Pleistocene. A southward migration of Tertiary fauna and flora accompanied the cooling trend, and the rate and degree of this migration is best recorded in the history of fossil plants. The second major factor operating to produce climatic change is mountain building. In western North America mountain building disturbed atmospheric circulation and restricted moisture to areas closer to its source, the Pacific and Atlantic Oceans and the Gulf of Mexico. The time and degree of elevation of the western mountain ranges and the stage of the secular temperature trend provide the clue to Tertiary climatic interpretations in the arid Southwest.

General Tertiary Climatic Trend

The most recent compilation of data on the climatic trend of the Tertiary is that of Barghoorn (1951), which is expressed in graphic form in figure 2.2. This graph was prepared by comparing the modern geographic distribution of extant plant genera with the distribution of the same genera in the geologic past. In Pleistocene time the distribution of the genera is nearly the same as it is today with nearly 100 percent of extant genera living in the region of the deposit containing the fossil flora. During Eocene time, however, only about 20 percent of existing genera had the same distribution that they have today. The Eocene was a time of maximum warmth and humidity and thus a time of maximum northward extension of tropical and subtropical flora. The graph indirectly shows the rate and magnitude of the shift of flora under the influence of the world-wide trend of gradually decreasing temperatures.

The world-wide distribution of tropical and subtropical flora in early Tertiary time suggests a broad zone of warm, humid climate which was probably controlled by convectional circulation. This type of circulation is derived from the tropical oceans and gives rise to high warm-season precipitation such as that which now occurs in the summer months in the southeastern portion of North America. The presence of tropical and subtropical flora as far north as Oregon during early Tertiary time suggests the dominant influence of convectional circulation and summer moisture over most of the United States. The progressive retreat southward of tropical flora that began in middle Tertiary time suggests a basic change in the circulation pattern. As the northern polar region became progressively cooler, the decrease in temperature caused a pattern of cyclonic circulation (Aleutian Low) to develop over the North Pacific. This cyclonic cell brought winter moisture to the northwestern coast of North America and caused cyclonic storms to move from west to east into the interior. The winter precipitation brought with it the development of a new flora which began replacing the tropical and subtropical flora. In addition, cold fronts began moving down from the polar region with increasing frequency and intensity and pushed the tropical flora even farther southward. Both convectional and cyclonic circulation bring moisture into the arid Southwest today with warm-season and cool-season precipitation being about equal.

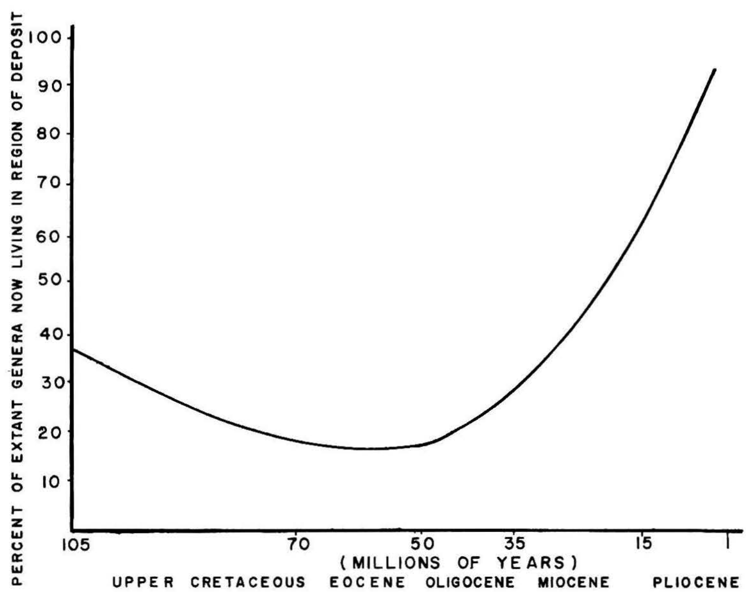

Figure 2. 2. --Graph relating percentage of genera in North American fossil flora to the same genera now native to the geographic region of the deposit. The lowest part of the curve represents a time of high temperature and maximum northern extension of tropical and subtropical flora. (After Barghoorn, 1951.)

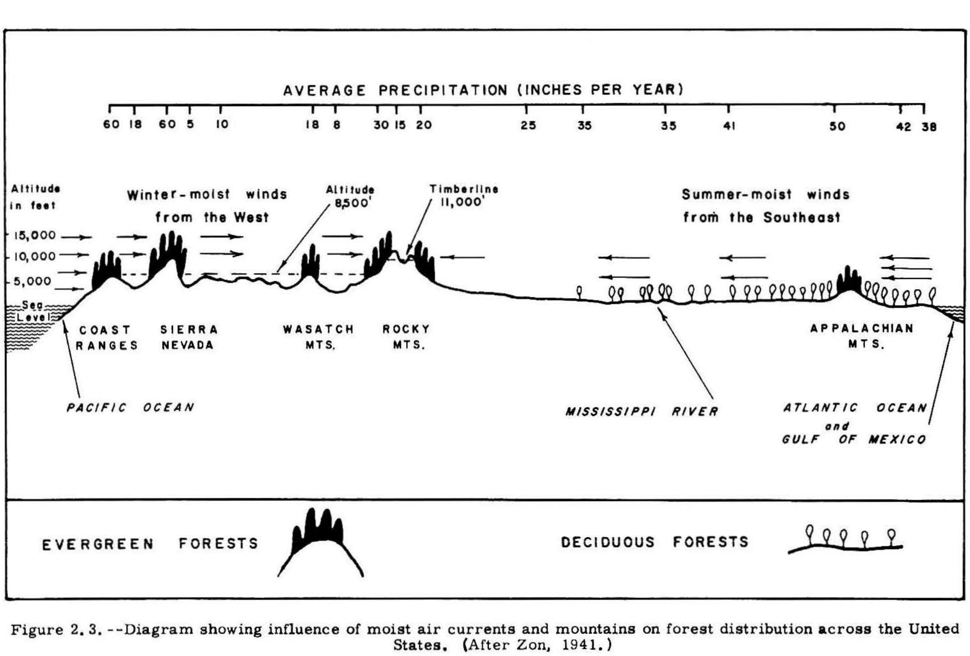

Figure 2. 3. --Diagram showing influence of moist air currents and mountains on forest distribution across the United States. (After Zon, 1941.)

Influence of Mountain Building

The erection of mountain barriers to oceanic circulation and the increased elevation that accompanies orogeny are dominant factors in the control of climate. A clue to an understanding of the effects of mountain barriers during Tertiary time is the present-day influence of mountain barriers on climate. The effect of intervening mountains on the distribution of moisture from marine sources and the distribution of modern forests along the 39th parallel in North America are shown graphically in figure 2.3. Cyclonic winter moisture moves in at all levels from the Pacific Ocean and gives rise to evergreen conifer forests on mountain slopes that are not in the rain shadow of a more westerly mountain range. This effect continues far inland, so that in the interior the highest peaks receive ample moisture today in spite of the high elevation of the Sierra Nevada. Moisture moves in from the Atlantic Ocean and the Gulf of Mexico principally during the warm season and gives rise to deciduous broadleaf forests. As the amount of moisture in the air diminishes toward the interior, the broadleaf forests become thinner and eventually give way to the grassland of the Great Plains. The interplay of winter moisture from the Pacific Ocean, summer moisture from the Atlantic Ocean and the Gulf of Mexico, and the rain-shadow effect of the intervening mountains control the distribution and character of modern forests. Analogous controls existed during Tertiary time, and by taking note of the time of erection of topographic barriers and the stage of development of the general climatic trend it is possible to estimate the climate of the arid Southwest for a given time in the Tertiary period.

LOWER AND MIDDLE TERTIARY CLIMATE IN THE WESTERN INTERIOR

During Eocene time the Rocky Mountains were a barrier to western moisture and the moderating effects of any circulation that may have come from the Pacific Ocean. Their existence is demonstrated in the appraisal of the ecology of the Green River basin by Wodehouse (1933). Wodehouse found abundant spruce, fir, and hemlock pollen as representatives of the upland flora at the same time that a subtropical flora was living at lower elevations. The suggested range in climate from cool temperate to subtropical indicates a considerable difference in elevation between the site of deposition and the surrounding highlands. Farther to the east, on the northern Great Plains, there existed a more continental climate than that which prevailed in the Green River area. Greater numbers of temperate genera from the Great Plains suggest an end to the moderating effect of oceanic atmospheric circulation and reflect the presence of the Rocky Mountains. After the development of the Rocky Mountains, the major topographic control of moisture into the Great Plains did not change during the rest of the Cenozoic Era. Subsequent climatic change in this region followed the general trend to cooler and less humid climate. The filling of the Gulf embayment augmented this trend by making the source of summer moisture even more remote. By early Pliocene time the climate of the southern Great Plains was only slightly warmer and had about 10 more inches of annual rainfall than at present (Chaney and Elias, 1936).

The present Sierra Nevada, Coast Ranges, and Cascade Mountains effectively stop Pacific moisture from reaching all but the highest peaks to the east. As each range was elevated, the climate to the east became more arid. It is the time and degree of elevation of these three mountain ranges that provide the key to the interpretation of climatic changes in the western interior. In the Eocene the Sierra Nevada was already exerting some control on the climate to the east, but Chaney (1940) believes that the ancestral Sierras were low enough to admit oceanic moisture to the Great Basin and that this moisture even found expression as far east as the Green River flora of Wyoming. Axelrod (1957) states that by Miocene time the summit level of the central and northern Sierra blocks lay near 3, 000 feet, which was still low enough to admit considerable moisture into the interior. The Tehachapi flora described by Axelrod (1939) shows that the southern end of the Sierra Nevada began rising in the middle Miocene, and Axelrod (1957) estimates a 5, 300- to 6, 000-foot uplift for the northern and central Sierras during the late Pliocene and early Pleistocene with the magnitude of uplift increasing southward. Chaney (1944) believes that the Cascade Mountains were in an early stage of growth at the beginning of the Pliocene and that further upbuilding had taken place by the middle of Pliocene time. The Coast Ranges are also thought to have begun rising at the end of the Miocene (LaMotte, 1936).

Farther to the west the elevation of the interior was important in controlling the development of climate. Temperature decreases with elevation, and in the western interior precipitation usually increases with elevation as the rain-shadow effect of other highlands is minimized. The cool highlands in the interior trapped high-level moisture and their permanent streams sometimes fed large lakes in the sheltered basins that they enclosed. MacGinitie (1953) said the Oligocene Florissant basin in the southern Rockies in central Colorado was an area of moderate elevation which was probably not less than 1, 000 feet nor more than 3, 000 feet above sea level. MacGinitie's estimate was based on a study of megafossils, which are poor representatives of the upland flora. Preliminary pollen studies by the writer suggest that the highlands surrounding the Florissant basin were at least 3, 000 feet in elevation and may have been higher because _Abies_ (fir) and _Picea_ (spruce), which are rare in the megafossil record, are a dominant part of the pollen flora. The Oligocene-Miocene oil shales near Elko, Nevada, also yield a pollen flora in which the upland genera _Abies_ (fir), _Picea_ (spruce), and _Tsuga_ (hemlock) are dominant, indicating cool, moist highlands above the general elevation of the interior basins. During early and middle Tertiary time it is probable that most of the western interior was an area of moderate elevation between 1, 000 and 3, 000 feet with occasional highlands up to several thousand feet higher. These cool highlands received ample moisture from over the ancestral Sierra Nevada and from the south and southeast, but the interior basins sheltered by these highlands were probably locally arid around their edges (Wodehouse, 1933).

During the Oligocene and Miocene the Colorado Plateau was probably at about the same general elevation (from 1, 000 to 3, 000 feet) as the basins in the rest of the western interior. The Colorado Plateau raised to a higher elevation near the end of Miocene time or in the earliest Pliocene. Pollen studies of the middle Pliocene Bidahochi Formation in northeastern Arizona have yielded some information about the climate and the elevation of the plateau after the Miocene-Pliocene uplift. Pollen has been isolated from the base of the upper member, which is late middle Pliocene in age (Repenning and others, 1958). Pine is dominant in the Bidahochi flora. In addition, _Ephedra_, chenopods, the aquatic _Sparganium_, and the algae _Pediastrum_ were present in the flora. Although several samples were treated and examined, _Artemesia_, which is a dominant form in the area today, was not observed. The dominance of _Pinus_ and the abundance of chenopods gives the flora a nearly modern aspect, but the presence of permanent water, the leaves of the plant _Robinia_, whose present occurrence is limited to warmer and more humid environments, and the absence of Artemesia suggest slightly warmer and more humid conditions than those that prevail in the area today.

Pinus (pinyon pine) is dominant in the modern flora of the plateau, and its best development occurs between 6,000 and 7,000 feet in northeastern Arizona (Deaver and Haskell, 1955). The pine pollen in the Bidahochi flora resembles that of Pinus edulis (pinyon pine) in size range and morphology, but species determination of pine pollen is uncertain at this time. The lower limit of all pine in Arizona is 4,000 feet above sea level (Kearney and Pebbles, 1951). The probable low relief of the Colorado Plateau in the Pliocene suggests that the source of pine pollen was not much higher than the site of deposition. Thus, it would seem that 4,000 feet would be a minimum estimate for the elevation of the plateau after the Miocene-Pliocene uplift and that in all probability the elevation was from one to several thousand feet higher than 4,000 feet above sea level.

The studies of mountain building and the general climatic trend suggest that during Eocene time and in the first half of Oligocene time the Southwest was experiencing a warm, humid, tropical climate. By Miocene time cyclonic moisture was being admitted from the west and northwest, and cooler temperatures had moved subtropical and warm temperate floras southward to make them dominant in the Southwest. In the middle Miocene the effects of increased elevation of the southern Sierra Nevada block were being felt in the form of increased aridity. Extreme aridity began at the beginning of the Pliocene and continued into the Pleistocene concomitant with the development of the Coast Ranges, Cascade Mountains, and the later Sierra Nevada orogeny. At the same time a combination of factors, including a continuation of the Tertiary trend to cooler temperatures, increased tectonic activity in the Basin and Range province, and the late Miocene-early Pliocene uplift of the Colorado Plateau had pushed subtropical climate further southward. In the Southwest at the present time an arid, subtropical climate exists only in the low southwestern corner of Arizona and the Sonoran desert, with almost all of the cooler climatic types present at higher elevations.

PLIOCENE-PLEISTOCENE (PRE-GLACIAL) CLIMATE

Cyclonic winter moisture from the North Pacific and convectional summer moisture from the south were probably as important in controlling the climate of the Pleistocene in the Southwest as they were in the late Tertiary period. The ideal places for the study of circulation changes are areas that are close to the source of moisture, and review of the Pliocene-Pleistocene information from these areas may aid in the understanding of the changes that took place in the interior. The Pliocene-Pleistocene deposits of California and the Gulf of Mexico are both well suited to the palynological study of climatic change. Information from the Gulf of Mexico is not yet available, but fortunately the California deposits have been studied in some detail.

The most useful index for the interpretation of climatic data from the Pliocene-Pleistocene interval has been a comparison of the temperature and moisture requirements of a fossil flora with the requirements of the flora living in the same area today. A modification of this concept is the comparison of the geographic position of a fossil flora with the position of its modern correlative. If a fossil flora is found south of its modern counterpart, it is assumed that temperatures were colder at the time of deposition of the fossil flora than at present. Similarly, if in a montane area a fossil flora is found at a lower elevation than its modern counterpart, the temperature was probably cooler during the deposition of the fossil flora. Along the west coast of North America there is a floral zonation based on the change from a cool and moist climate in Washington to a warm, dry climate in southern California. As the coastal flora shifted northward and southward in response to glacial changes, it left a record in the marine and nonmarine Pliocene and Pleistocene deposits. The geographic position of a fossil flora can be used to infer the degree of temperature and moisture change at the time of deposition of the fossil flora. Indirectly, the changes in the cyclonic circulation cell (Aleutian Low) of the North Pacific can also be inferred because the coastal climate is largely the result of the activity of this cell. The coastal flora had been shifting southward during the middle and late Tertiary period, and the time at which it moved south of its present position is an index for detecting the cooling effects associated with the building up of the first ice sheet. The time at which land temperatures as cool as those existing today was first achieved in northern latitudes would probably be associated with the cooling effects of ice accumulation, because there is now considerable ice in the Arctic regions. Furthermore, the amount of southward shift would be an indirect measurement of the intensity of cyclonic activity in the Aleutian and, perhaps, Icelandic Lows. It is now known that the activity of these lows is a function of polar coldness and the temperature differential between the polar region and the marine embayment of the North Pacific and North Atlantic, and that these factors were important in controlling ice accumulation.

During Pleistocene time in coastal California there were intervals of a more humid and cooler climate than exists at present. Chaney and Mason (1934) concluded that the Pleistocene Santa Cruz Island flora of southern California represents a shift of 400 miles south of its modern counterpart and may reflect one of the glacial stages. The Pleistocene Carpenteria flora described by Chaney and Mason (1934) indicates a shift of 200 miles to the south. A Pleistocene pollen flora was found by the writer in a lignite bed beneath a terrace in Monterey Bay, California. This flora contained both Abies (fir) and Picea (spruce), whose present southern limit is about 200 miles to the north. A southward floral shift of up to 300 miles may have been possible because of the high frequency of Picea (spruce) pollen in the lignite. These three studies suggest that the coastal flora of California shifted at least 300 miles south of their present positions during glacial stages.

There is considerable evidence that later Pliocene flora was also present at lower latitudes than its modern counterparts. Dorf (1933) found that the upper Pliocene Santa Clara flora represented conditions that were more humid and cooler than at present, or similar to a type of climate that is now found north of the position of the fossil flora. The upper Pliocene Sonoma flora has a close relationship to a modern flora which occurs about 80 miles north of the fossil locality (Axelrod, 1944). A pollen flora was found by the writer in the marine middle Pliocene Purissima Formation at San Gregorio Beach, California. The deposit contains abundant Abies (fir) pollen along with high frequencies of Pinus (pine). The present southern limit of Abies (fir) is about 150 miles to the north, and its presence in the Purissima flora suggests a southward extension of moist climate as early as middle Pliocene time.

Pollen from the Merced Formation near San Francisco shows that there is little climatic change at the stratigraphic transition between the Pliocene and Pleistocene. The Merced Formation of Pliocene and Pleistocene age has its type section on the San Francisco Peninsula and was described by Lawson (1896) as consisting of over 5,000 feet of well-exposed marine sands, silts, and clays. Pollen was obtained by the writer from a peaty bed in the upper part of the formation which Lawson considered to be Pleistocene in age. The pollen of ecological significance in the Merced flora are those of Picea cf. sitchensis, Abies grandis, and Tsuga heterophylla. The southern limit of these three species is now about 100 miles to the north. The low frequencies of Picea (spruce), Abies (fir), and Tsuga (hemlock) and the similarity of the Merced pollen flora to the nearby Pleistocene Tomales Bay flora of Mason (1934), which represents an 80- to 100-mile southward shift, suggest that the Merced pollen flora does not represent more than a 100-mile southward shift of the flora during the earliest Pleistocene. When compared with the 300-mile estimate for the maximum southward floral advance during the Pleistocene, the Merced pollen flora does not represent a time of maximum cooling. The climate of the early Pleistocene in coastal California was apparently a continuation of the climate of the upper Pliocene with the major part of the glacial cooling taking place later in the Pleistocene.

As the general cooling trend of the Tertiary continued from Eocene time to within the Pleistocene, a time was eventually reached in or at the end of the middle Pliocene when the climate was cooler than that which exists in coastal California today. Throughout the middle and later Tertiary period the cyclonic cell which brings Pacific moisture to the West Coast was increasing in intensity and shifting southward. By late Pliocene time it had delivered a cool, moist climate which contained the components Abies (fir), Picea (spruce), and Tsuga (hemlock) as far south as San Francisco. Some of the cooling effect of this cyclonic cell, which was then south of its present position, may have been transmitted to the interior and felt in the Southwest. In Pleistocene time the cyclonic cell became even more well developed and shifted even farther south to bring a cool, moist climate to the central and southern part of California, and it may have been responsible for bringing moisture to the interior at high levels to contribute to the formation of the Pleistocene lakes.

Pliocene-Pleistocene climatic information from areas which derive their moisture from the Gulf Coast or the Atlantic Ocean is not available. The lower Pliocene flora of Beaver County, Oklahoma, is indicative of greater precipitation and higher mean annual temperature than that which now prevails in the area (Chaney and Elias, 1936). The small upper middle Pliocene Bidahochi pollen flora from northeastern Arizona, an area which receives about two-thirds of its annual rainfall in the warm season, represents conditions which were nearly modern but probably slightly warmer and more humid than at present. The deeper part of two cores from the Valley of Mexico is believed to represent the top of the Pliocene Taranga Formation by Bryan (1948) and Arellano (1951). Sears and Clisby (1955) believe that the pollen flora in both cores shows evidence of higher temperature and moisture at their lower levels. The implication from these few studies would be that the Tertiary trend of decreasing temperatures in areas that derive moisture from the Gulf of Mexico did not reach a point where the temperatures were cooler than at present until after the end of the Pliocene, or much later than an area like California which derives cyclonic moisture from the Pacific Ocean. The dating of the deeper parts of the two cores, however, is indirect, and there is a distinct possibility that they may actually represent some part of the Pleistocene.

SUMMARY

The Tertiary climate in the Southwest has its source in the Gulf of Mexico, the Atlantic Ocean, and the Pacific Ocean. In early Tertiary time convectional moisture from the Gulf and tropics brought heavy rainfall and warm temperatures into the Southwest and brought about the development of tropical and subtropical flora. By middle Tertiary time the trend toward cooler temperatures was on the way, and a cell of cyclonic circulation over the Pacific Ocean was bringing cool-season moisture into the Southwest. In the middle Miocene, as the southern end of the Sierra Nevada began rising, the Southwest was caught in its rain shadow and began to be increasingly arid. By the middle Pliocene the Cascade Mountains and the Coast Ranges were interfering with circulation and the Sierra Nevada had reached new heights. In spite of the increased strength of the cyclonic circulation cell due to the cooling trend in the Tertiary, the Southwest had taken on an arid character similar to that which exists today. The filling of the Gulf of Mexico and the further restriction of convectional circulation accentuated the trend to more arid climate. Orogeny in the Basin and Range and the Colorado Plateaus provinces near the end of Miocene time raised the general ground elevation to encounter cooler temperatures. Now a dry, subtropical climate exists only in the low southwestern portion of Arizona and in the Sonoran desert. The Pacific cyclonic cell had intensified and shifted southward by late Pliocene time and probably brought more moisture to the high peaks and uplands in the arid Southwest than is derived from the same source today, a trend which may have culminated in the development of the interior lakes in the Pleistocene.