A Paleobotanical Interpretation of Tertiary Climates in the Northern Hemisphere: Data from fossil plants make it possible to reconstruct Tertiary climatic changes, which may be correlated with changes in the inclination of the earth’s rotational axis

Author(s): Jack A. Wolfe

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A Paleobotanical Interpretation of Tertiary Climates in the Northern Hemisphere

Data from fossil plants make it possible to reconstruct Tertiary climatic changes, which may be correlated with changes in the inclination of the earth’s rotational axis

Anyone who has even a slight acquaintance with paleoclimatic literature is well aware that the last 1 to 1.5 million years of the Quaternary have been characterized by major episodic glaciations of the continents of the Northern Hemisphere, and hence the period is atypical of much of geologic time. A commonly accepted thesis on climates preceding Quaternary glaciation is that, from some time in the Late Cretaceous or early Tertiary (some 40–80 m.y. ago), when the earth’s climate was characterized by generally higher temperatures and higher equability of temperature than now, both overall temperature and equability have gradually decreased, culminating in Quaternary glaciation. Further, some researchers have maintained that even as long ago as the early Tertiary, temperatures were only moderately higher than now, even at high latitudes. (See Table 1 for the geologic time span dealt with in this article.)

An increasing accumulation of data from a multitude of sources has, however, largely negated such once commonly accepted theses. A significant warm episode during the Miocene (see Fig. 1) was first documented in Europe by Mai (1964) and has subsequently been substantiated in other regions such as Japan (Tanai and Huzioka 1967), western North America (Wolfe and Hopkins 1967; Addicott 1969), and New Zealand (Devereux 1967). Alpine glaciation is known to have begun in Alaska during the Miocene (Denton and Armstrong 1969; Pfafker and Addicott 1976), when at least part of the Antarctic ice sheet was also present (Kennett 1977).

The most dramatic climatic event, however, occurred during the middle of the Tertiary. MacGinitie (1953) recognized that, if certain floras in Oregon were as close in time as some stratigraphic evidence indicated, a rapid and major climatic change must have occurred, a decrease in temperature that was considered significant but gradual by Nemec (1964) and Zhilin (1966). Utilizing newly available radiometric ages, Wolfe and Hopkins (1967) demonstrated that this major climatic deterioration had occurred within 1 or 2 m.y.

This temperature decrease has subsequently been recognized in many regions. I had previously (1971) termed it the “Oligocene deterioration,” but since recent work in relating the marine and nonmarine chronologies indicates that, in the widely accepted chronology based on marine plankton, the event occurred at the end of the Eocene, I will refer to it as the “terminal Eocene event.” In the Southern Hemisphere, the terminal Eocene event is closely associated with the initiation of cold bottom water in the oceans (Kennett 1977), while on the continents of the Northern Hemisphere the event is emphasized by a major decrease in equability of temperature (Wolfe 1971).

Foliar physiognomy

A thorough review of all pertinent paleoclimatic data for the Tertiary would be a lengthy and prodigious task. In this paper I will largely limit the discussion to the paleoclimatic data based on fossil plants from middle to high latitudes (c. 30°) of the Northern Hemisphere. For the Paleocene and Eocene, the North American data, which are based on leaf remains, are the most relevant. In Europe, the major Eocene floral sequence is based on fruit and seed floras. In eastern Asia, some Oligocene floras have been described (Tanai 1970), but most of the Paleocene and Eocene assemblages remain undescribed and unanalyzed (Tanai 1967).

There are several advantages in basing paleoclimatic interpretations on

Table 1. The subdivisions of the Cenozoic Era

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the physical aspects (or physignomy) of fossil leaf assemblages. The physical characteristics of vegetation occupying similar climates in widely separated regions are highly similar, although the regions may have only a few taxa in common. Among the most conspicuous of such characteristics are the similarities in the appearance of foliage. On the other hand, vegetation occupying dissimilar climates in one region typically has different physical characteristics, although many taxa may occur throughout the region.

Thus the environment tends to select plants that have certain physical aspects for a given climatic type, whether this climatic type is separated by oceans or, presumably, by major periods of time. Just as we can expect the Tropical Rain forest in Africa to have the physical characteristics of Tropical Rain forest in other regions of the world, so we can also expect the present Tropical Rain forest to have the physical characteristics of the Tropical Rain forest of the Eocene.

On the other hand, the Tropical Rain forest of Indonesia has a floristic composition markedly different from the composition of the Tropical Rain forest of Brazil. Such differences have resulted from a variety of historical factors, both geographic and evolutionary. These historical factors will also result in floristic differences between the Tropical Rain forest of the Eocene in a given region and any part of the modern Tropical Rain forest. Considering that the floristic composition of any vegetational type is continually undergoing change, then the determination of the vegetational type (and hence climatic type) represented by a fossil assemblage is best accomplished by analyzing the physical characteristics of the assemblage rather than its floristic composition. And, the further back in time, the more dissimilar the floristic associations are to present associations and the more problematic become climatic inferences.

Among the most useful physignomonic characters of broad-leaved foliage are: type of margin, size, texture, type of apex, and type of base and petiole (see Fig. 2). In areas of high mean annual temperature and precipitation, for example, leaves typically have "entire" margins (i.e. lacking lobes or teeth), are large, are coriaceous ("leatherlike")—an indication of an evergreen habit, and have a high proportion of attenuated apices (i.e. "drip-tips," particularly common on lower-story plants); and a moderate number have cordate (heart-shaped) bases associated with palmate venation and joints ("pulvinar") in the petiole—a combination of characters typically associated with the vine, or liana, habit.

The general correlation between type of leaf margin and climate was first
documented by Bailey and Sinnott (1915) and has since been sporadically applied to interpretations of fossil assemblages. A recent compilation of analyses of woody vegetation in the humid to mesic (moderately humid) forests of eastern Asia has shown a strong correlation between the percentage of species with entire leaf margins and mean annual temperature (Fig. 3). Compilations of leaf-margin data of secondary vegetation—vegetation on disturbed sites that has not reached a climax stage—and of the broad-leaved element in coniferous forests do not display such a correlation.

Although leaf size is an important criterion in studies of extant vegetation, the application of this parameter to fossil assemblages is highly problematic, because leaves of different sizes may be differentially selected in the process of transport and preservation (Spicer 1975). Further, leaf-size changes can be related to precipitation and soils as well as to temperature. In the following discussion, I have used a generalized and modified version of the Raunkiær (1934) system of leaf sizes: mesophyll for the larger mesophyll and larger classes, notophyll for the smaller mesophyll class (Webb 1959), and microphyll for the smaller classes.

The significance of physiognomy to the paleobotanist attempting paleoclimatic reconstructions is that the major physiognomic subdivisions of vegetation (which are partly based on foliar characters) have been found to correspond closely with certain major temperature parameters (Wolfe, in press). Figure 4 shows that mean annual temperature (an approximation of heat accumulation) is of major significance in determining what type of vegetation prevails, as are warm-month means. Only two cold-month means are of major significance. The 1°C mean separates dominantly broad-leaved evergreen (above 1°C) from broad-leaved deciduous (below 1°C) forests; in the areas that have cold-month means between 1°C and −2°C, notophyllous broad-leaved evergreens occur as an understorey element, and in regions of even greater winter cold, notophyllous broad-leaved evergreens are lacking. The 18°C cold-month mean—a commonly accepted boundary between “tropical” and “subtropical”—has no relevance to the distribution of vegetation.

Estimates of mean annual temperature can be based on the percentage of entire-margined species in a given fossil assemblage. More difficult to infer is the mean annual range of temperature, which, in some cases, can be estimated only within broad parameters. In other cases, however, mean annual range of temperature can be accurately inferred. For example, if two succeeding assemblages have the same leaf-margin percentage of 50% (mean annual temperature ~17°C), and if the younger assemblage is dominantly microphyllous and the older assemblage is dominantly notophyllous, then reference to the framework of Figure 4 indicates that a mean annual range of temperature of 6°C was reached some time between the two assemblages. A second example is that of the Miocene Seldova Point flora, which represents vegetation slightly inland from the coast of southern Alaska. Foliar physiognomic (as well as floristic) criteria indicate a mean annual temperature of 6–7°C (Wolfe and Tanai, in press). Other paleobotanical data indicate that the broad-leaved deciduous forest represented by the Seldova Point flora merged with coniferous forest toward the coast. Again, reference to Figure 4 indicates a mean annual range of temperature of about 26–27°C.

Two major problems that have hampered many climatic inferences from paleobotanical data have been the lack of floras in even moderately close stratigraphic successions and the total misinterpretations of the age and climatic significance of high-latitude Tertiary floras. These misinterpretations arose from acceptance of the undocumented concept of an “Arcto-Tertiary Geoflora”—that the Eocene vegetation in Alaska represented temperate broad-leaved deciduous forest that, unchanged, gradually migrated southward to middle latitudes. In North America, both problems have, to a high degree, been overcome. In Alaska there are stratigraphic sequences of florases—many independently dated—that represent most of the Tertiary. In the Pacific Northwest, numerous florases—again, many in stratigraphic succession and/or independently dated—occur in early Eocene and younger rocks. In the Mississippi embayment region, an almost complete sequence of florases represents most of Paleocene and Eocene time. Almost all these florases represent coastal plain vegetation, and thus one major variable in interpreting the significance of paleoclimatic inferences—altitude—is held approximately constant. Certain florases from interior areas add other dimensions to paleoclimatic models, but the altitu-
Figure 4. The humid to mesic forests of the Northern Hemisphere can be approximately circumscribed by various major temperature parameters. By comparing leaf assemblages in southern Alaska and the Pacific Northwest to the modern vegetation, we can infer the mean annual temperature and mean annual range of temperature for the assemblages. Major changes in temperature parameters are indicated for the time span between the middle Eocene and the Quaternary—showing a dramatic increase in mean annual temperature and an increase in mean annual range of temperature during the terminal Eocene event.

Paleocene and Eocene climates

The most complete sequence of Paleogene leaf floras in a small area is that of the Puget Group in western Washington (Wolfe 1968). The Puget assemblages extend from an estimated 50 m.y. ago (late early Eocene) up to about 34 m.y. ago (latest Eocene). In this sequence, the floras all contain numerous leaf species that have drip-tips and/or probable liana leaf physiognomy, and coriaceous (i.e., evergreen) texture dominates. Thus, all the assemblages represent vegetation that apparently grew under abundant year-round precipitation and would be classed as broad-leaved evergreen rain forests. Major changes in margin and size of the leaf assemblages occurred, however, during deposition of the Puget Group (Fig. 5). The leaf-margin data alone indicate major (perhaps 7-8°C) fluctuations in mean annual temperature, and, in a general manner, the leaf-size data also indicate climatic fluctuations. Sequences of floras in western Oregon, eastern Oregon, and northeastern California parallel the Puget sequence (Wolfe 1971).

The Puget leaf-size data are, however, possibly significant in a context other than mean annual temperature. In the lower part of the sequence, although the leaf-margin data do not significantly change, there is a pronounced movement from a nontypical to a microphyllous forest. If mean annual temperature was approximately constant during this interval, then mean annual range of temperature must have decreased (i.e., equability of temperature increased). Indeed, the combination of physiognomic data indicates a mean annual range of temperature about half that at present in coastal western Washington, which is highly equable now in comparison to most other mid-latitude areas of the Northern Hemisphere. Although other workers have on questionable floristic interpretations (e.g., Berry 1914, p. 66-67) suggested that the Eocene was characterized by high equability, the Puget physiognomic data provide strong evidence that the Eocene was in fact highly equable.

One of the major corollaries of high equability during the Eocene has been generally overlooked, particularly by the proponents of the concept of an “Arcto-Tertiary Geoflora,” who long argued that the Eocene vegeta-
tion in regions such as Alaska represented temperate broad-leaved deciduous forest. As in the now highly equitable areas of the Southern Hemisphere or on tropical mountains, temperate and mesic broad-leaved deciduous forests could not have existed in the Northern Hemisphere during the Eocene. That is, the latitudinal temperature gradient would fall far to the left side of Figure 4—far from temperatures that would support temperate broad-leaved deciduous forest.

Notable also in the Puget analyses is that, during the late middle Eocene (ca. 45 m.y.), the vegetation was marginally Tropical Rain forest. A contemporaneous assemblage in northern California—the Susanville flora (lat 40°)—has a leaf-margin percentage of 82, concomitant with a leaf-size index of 79. The other physiognomic data are consistent with inferring the Susanville flora to be Tropical Rain forest. This indicates that Tropical Rain forest (and the 25°C isotherm) occurred at least 20° and possibly 30° poleward of the present northern limit.

Many assemblages that those who argued for an “Arcto-Tertiary Geo-flora” interpreted as temperate broad-leaved deciduous forest are indeed that type; however, these assemblages are typically of Neogene age (cf. the radiometric data of Triplehorn et al. 1977), rather than Eocene, as they had supposed. In fact, only two small Eocene assemblages were known from Alaska until the last decade.

Collections from the Eocene at 60–61° latitude in the Gulf of Alaska region (Wolfe 1977) represent the latter half of the epoch. The late middle Eocene floras—correlative with the Susanville flora—represent Paratropical Rain forest and indicate the warmest climate (ca. 22°C mean annual temperature) of the Tertiary in Alaska (Wolfe 1972). The warmth indicated by the foliar physiognomic data is fully substantiated by the floristic evidence: included are feather and fan palms, mangroves, and members of other families now dominantly or entirely tropical (Wolfe 1977).

Recent geologic data (e.g. Jones et al. 1977) indicate that parts of southern Alaska were once at low latitudes and have drifted northward. The drift and accretion of these plate fragments to Alaska were, however, accomplished by the beginning of the Tertiary. The various major models of plate tectonics are unanimous in suggesting that, in general, western North America rotated southward during the Tertiary. That is, the paleolatitudes of these western North American floras were probably higher than the present latitudes of the fossil localities.

The latitudinal temperature gradient along the Pacific Coast of North America is today very moderate—about 0.5°C/1° latitude. During the late middle Eocene, however, the gradient was even lower. The Susanville (ca. 27°C mean annual temperature at 40° N.), the Puget (ca. 25°C mean annual temperature at 48° N.), and the Gulf of Alaska (ca. 22°C mean annual temperature at 60° N.) data indicate a temperature gradient of about 0.25°C/1° latitude.

The Alaskan Paleocene assemblages are exceedingly difficult to interpret climatically. In southeastern Alaska on Kupreanof Island (lat 57°) there are large assemblages that in all aspects of physiognomy represent Notophyllous Broad-leaved Evergreen forest (mean annual temperature approximately 18°C). Yet, only 2–4° latitude northward, the bulk of the broad-leaved evergreen element is unrepresented in the even larger assemblages of the Chickaloon and West Foreland formations. In features of foliar physiognomy such as margin and size, the Chickaloon assemblages would appear to correspond to Notophyllous Broad-leaved Evergreen forest (Wolfe 1972), yet the Chickaloon assemblages are dominantly broad-leaved deciduous, and even the broad-leaved deciduous element is not as diverse as in present temperate broad-leaved deciduous forests. The minor broad-leaved evergreen element includes palms and certain dicotyledonous families that are not to be expected in temperate broad-leaved deciduous forests. Thus, although almost all physiognomic characters and limited floristic data point to temperatures that should support dominantly broad-leaved evergreen vegetation, the vegetation was dominantly deciduous. Such assemblages occur throughout much of Alaska and Siberia north of latitude 60° during the Paleocene.

In the southeastern United States a large number of Paleogene leaf assemblages that represent coastal plain vegetation occur. Detailed work by many stratigraphers allows an accurate placement of these assemblages in stratigraphic sequence (Fig. 6). The oldest assemblages—early Paleocene (Midway Group)—are
those from Naborton and Mansfield, Louisiana. The physiognomy of these assemblages is clearly indicative of Tropical Rain forest (mean annual temperature about 27°C). The succeeding late Paleocene (lower part of Wilcox Group) assemblages represent Paratropical Rain forest—an indicated cooling consonant with data from the continental interior (Wolfe and Hopkins 1967). In the earliest Eocene assemblages (upper part of Wilcox Group), however, leaf size is reduced, the probable liana type of leaf is not as common as earlier, and drip-tips are uncommon; at the same time, the leaf-margin data suggest a warm interval.

How much of a hiatus exists between the Wilcox and Claiborne assemblages is uncertain, but I am assuming that most of the late early and early middle Eocene is missing, at least in the floral sequence. The large assemblages from Puryear, Tennessee, and Granada, Mississippi (the bulk of the “Wilcox flora” of various authors, but actually Claiborne in age; cf. Dilcher 1973a), are of late middle Eocene age. Dilcher (1973b) considered the climatic inferences based on such assemblages to be puzzling; however, the scarcity of probable lianas, the scarcity of drip-tips, and the small leaf size concomitant with a high leaf-margin percentage are characteristic of dry tropical vegetation (cf. Rzedowski and McVaugh 1966).

It is perhaps also significant that these Claiborne assemblages contain a diversity of Leguminosae, a family common in dry tropical vegetation today. Apparently a cooling occurred near the Claiborne-Jackson boundary, but the one cool assemblage (interestingly, once interpreted by Berry, 1916, to be of Pleistocene age) is unfortunately small. In any case, the Mississippi embayment sequence indicates a pronounced drying trend from the Paleocene into at least the middle Eocene.

In the continental interior, the Paleocene floral sequence also shows a definite cooling from the early into the late part of the epoch (Wolfe and Hopkins 1967; Wolfe, in press). Hickey (1977) suggests a renewed warming trend near the Paleocene-Eocene boundary, which would parallel the Mississippi embayment trend. As in that area, the interior Paleocene assemblages all indicate humid to mesic vegetation.

In the Eocene, however, the pattern in the interior becomes greatly complicated. The late early and early middle Eocene assemblages (the earliest Eocene assemblages are unstudied) from central and northern Wyoming represent definite mesic conditions, but the assemblages from southern Wyoming and adjacent Colorado and Utah represent pronounced dry conditions (MacGinitie 1969, 1974). How this situation is related to the presence of mountains and consequent rain shadows is uncertain. Today, the predominant sources of moisture for this region are southerly; one would expect the more southern area (southern Wyoming) to be moister if the Eocene circulation pattern were similar. Later Eocene leaf assemblages from this region are poorly known, except for the latest Eocene Florissant flora of central Colorado (MacGinitie 1953). The climatic significance of this flora is problematic because the altitude at which the Florissant beds were deposited is unknown.

To the west, a number of floras are known from an ancient uplifted area that stretched from Nevada north into British Columbia. The known assemblages represent mesic coniferous forest. Two—the Princeton, British Columbia (Arnold 1955), and the Republic, Washington (Berry 1929)—are of early middle Eocene age and represent the same cool interval as documented in western Washington. The Copper Basin and Bull Run floras from northern Nevada (Axelrod 1966) are correlative with the late Eocene cool interval.

The Paleocene and Eocene floras from North America thus provide the basis for a number of climatic inferences. (1) An overall gradual warming took place from the Paleocene into the middle Eocene, with gradual cooling until the terminal Eocene event. (2) Cool intervals occurred during the late Paleocene, the late early to early middle Eocene, and the early late Eocene. The difference between the intervening warm intervals was, in mean annual temperature, about 7°C. (3) The cool intervals were about 4 to 5°C (mean annual temperature) warmer than the present. (4) Mean annual range of temperature during the middle Eocene was about half that of the present. (5) Mean annual range of temperature decreased from the early into the middle Eocene and possibly increased slightly until the end of the Eocene. (6) The latitudinal temperature gradient during the middle Eocene along the west coast of North America was about half that of the present. (7) The west coast of North America received abundant precipitation during that period. (8) The southeastern United States experienced a pronounced drying trend from the Paleocene into at least the middle Eocene.

Oligocene and Neogene climates

The most profound climatic event of the Tertiary took place at the end of the Eocene. In middle to high latitudes of the Northern Hemisphere, the vegetation changed drastically. Within a geologically short period of time, areas that had been occupied by broad-leaved evergreen forest became occupied by temperate broad-leaved deciduous forest. A major decline in mean annual temperature occurred—about 12–13°C at latitude 60° in Alaska and about 10–11°C at latitude 45° in the Pacific Northwest. Just as profound, however, was the
shift in temperature equability: in the Pacific Northwest, for example, mean annual range of temperature, which had been at least as low as 3–5°C in the middle Eocene, must have been at least 21°C and probably as high as 25°C in the Oligocene (Fig. 4; Wolfe 1971).

One of the major aspects of early Oligocene floras at middle to high latitudes is their lack of diversity, which was followed by enrichment during the remainder of the Oligocene (Wolfe 1972, 1977). The lack of diversity would be expected following a major and rapid climatic change such as the one that characterized the terminal Eocene event—that is, few lineages were preadapted or could rapidly adapt to the new temperature extremes.

Although the late early to early middle Miocene warming has been recognized throughout the world, some evidence indicates a warm interval during the late Oligocene (see references cited by Wolfe 1971) and perhaps, to a lesser extent, a warming during the latest Miocene (Wolfe 1969; Barron 1973). These warm intervals, however, were not as warm in comparison to adjoining cool intervals as were the Paleocene-Eocene warm intervals.

The climatic trends following the terminal Eocene event, aside from the minor fluctuations, are of great significance. One trend that can be demonstrated in areas north of latitude 30° is an increase in equability, a trend that runs counter to putative models of Neogene climatic change (cf. Axelrod and Bailey 1969).

Mean annual range of temperature was, during the Oligocene in western Oregon, as great as 21–25°C, but the present value is 12–16°C. At latitude 60° in Alaska, the mean annual range of temperature during the Miocene warm interval was at least as high as 26–27°C, in contrast to the current value of 18°C in the same area (Fig. 4). Similar declines in mean annual range of temperature can be demonstrated in other areas of the Northern Hemisphere, for example, in eastern Asia (Wolfe and Tanai, in press).

Overall trends in mean annual temperature since the terminal Eocene event are dependent on latitude. In southern Alaska (lat 60°), a decline of about 4°C can be documented since the early to middle Miocene. The salient feature of this high-latitude trend is that almost all the change appears to be the result of a decline in summer temperature, which would greatly enhance the “over-summering” of snow fields and, in turn, the initiation of widespread glaciation.

In the Pacific Northwest (lat 42–46° N.), no overall change in mean annual temperature appears to have occurred since the terminal Eocene event. In California and Nevada, climatic inferences from Neogene floras are so greatly complicated by altitudinal and rain shadow factors that extension of these inferences to other areas would at present be unjustified. The few Neogene floras based on leaf remains from eastern North America are too small to be of value in this context.

In Europe, the Neogene floras are found at about the same or higher latitudes as those in the Pacific Northwest; correcting for plate tectonic movements, the Pacific Northwest and European Miocene floras would have been at about equivalent latitudes. The European Neogene sequences typically display—as in the Pacific Northwest—an overall change from broad-leaved deciduous (with a broad-leaved evergreen element, particularly in the Miocene warm interval) to coniferous forest. This implies predominantly a decrease in mean annual range of temperature, possibly along with some decline in warm-month and consequently in mean annual temperatures.

In eastern Asia, the assemblages from Sakhalin (lat 50°) and Kamchatka (lat 55°) show much the same temperature trend as those in Alaska, whereas in Hokkaido (lat 42–45°) only a decrease in mean annual range of temperature occurred (Wolfe and Tanai, in press). South of Hokkaido the floras of Oligocene and Neogene age apparently indicate a contradictory trend—at least in part. In the early Miocene, for example, broad-leaved deciduous forest occupied lowland Kyushu (lat 32°) and southern Honshu (lat 35°; Tanai 1961)—areas now occupied by broad-leaved evergreen forest. Although it can be inferred that mean annual range of temperature has decreased by about 2–4°C, the major point is that mean annual temperature has increased by 3–4°C (Fig. 7). In the middle Miocene of northern Taiwan (lat 25°)—an area now occupied by Paratropical Rain forest—the lowland vegetation was Notophyllous Broad-leaved Evergreen forest (Chaney and Chuang 1968), indicating an increase of at least 2°C in mean annual temperature.

It is significant in this context that Muller (1966) has recorded pollen of elements such as alder and spruce from Borneo (lat 5°), while Graham and Jarzen (1969) have recorded similar cool-climate indicators from the Oligocene to the Miocene in Puerto Rico (lat 18°). In these instances the authors explained the presence of the cool element by suggesting the existence of mountains even higher than those now in the respective areas—although there are no geologic data to support such inferences. Graham (1976), however, explained the presence of cool-climate indicators in the Miocene of Vera Cruz (lat 19°) by suggesting that temperatures were cooler than now. I suggest that the presence of cool-climate indicators is consistent with the data from Taiwan and Kyushu and implies that, following the terminal Eocene event, low latitudes were cooler than at present.

It is noteworthy that the amount of change in mean annual range of temperature increases as latitude gets higher. At lower latitudes, the major change was apparently an increase in winter temperature that resulted in an overall increase in mean annual temperature and a slight decrease in mean annual range. At about 45° latitude, winter temperature increased by about the same amount as summer temperature decreased, with the result that mean annual temperature remained constant while mean annual range decreased moderately. At high latitudes, summer temperature decreased significantly, leading to a moderate decrease in mean annual range.

One of the obvious consequences of the above trends is an increase in the latitudinal temperature gradient. Such an increase would necessarily increase the intensity of the subtropical high-pressure cells (Willett and Sanders 1959), which, in turn, would bring increasing drought—particularly in summers—to the west coasts of the continents. Such an increase in

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Milankovitch (1938) proposed that the episodic glaciations of the Quaternary resulted from changes in the inclination of the earth’s rotational axis. The changes Milankovitch considered were those due to perturbations, precession, and other known phenomena that result in minor changes in the inclination. In turn, inclinational changes would cause changes in insolation (the amount of radiation received from the sun) that would vary according to latitude. These astronomical explanations of Quaternary climatic change have received considerable support from many researchers, who consider that the paleoclimatic data fit well the timing based on calculations of minor inclinational changes.

Is it entirely coincidental that the divergent latitudinal patterns following the terminal Eocene event fit very well a model resulting from a significant decrease in the inclination of the earth’s rotational axis? According to Milankovitch’s hypothesis, under conditions of decreasing inclination (and assuming an atmospheric circulation pattern similar to that of the present), the pattern of climatic change would be (1) an increase in winter temperatures at lower latitudes (resulting in an increase in mean annual temperature), (2) an increase in winter temperatures about equal to a decrease in summer temperatures at latitude 43° (resulting in no increase in mean annual temperature), (3) a decrease in summer temperatures at higher latitudes (resulting in a decrease in mean annual temperature), and (4) a decrease in mean annual range of temperature proportional to the latitudes.

These are precisely the changes that are inferred from paleobotanical data for the Oligocene and Neogene and would indicate that a significant decrease in the earth’s inclination has occurred during the last 30 million years.

Conditions during the Paleocene-Eocene were strikingly different from those during the Oligocene and younger epochs. During the thermal and equatorial maximum of the middle Eocene, the west coast of North America was wet and the southeastern United States was comparatively dry. The presence of humid broad-leaved evergreen forests in Alaska would, concomitant with the other data, argue for a circulation that involved the poleward flow of warm, moist air along the west coast; as this flow returned equatorward over the eastern part of the continent, the heating air would, of course, become drier. That is, the Eocene pattern may have been dominated by north-south (meridional) flow rather than being dominated by regional cells, as at present. What factor(s) could bring about such a pattern?

Readers who are plant physiologists may have been startled to learn that during the Eocene, broad-leaved evergreen forest extended north of latitude 60°. The principles of plant physiology would argue against such vegetation under the prolonged dark winters at such latitudes (Mason 1947; van Steenis 1962). The present distribution of broad-leaved evergreens is consistent with such principles—that is, notophyllous evergreens occur on mountains in California that have the same fundamental temperature parameters as lowland areas at more northern latitudes, where notophyllous broad-leaved evergreens are absent (Wolfe, in press). Notophyllous broad-leaved evergreens—except for a very few conspicuous taxa—today do not occur north of 50° latitude, and most are equatorward of 40°-45°. Such considerations provide strong evidence that the middle Eocene Alaskan assemblages, with their diverse and dominant notophyllous to mesophyllous broad-leaved evergreen element, could not have existed under the present light conditions at the latitude of the fossil localities. Light was, in fact, considered a negative factor in the possibility of explaining trans-Pacific disjunctions of tropical broad-leaved evergreen groups via the land bridge that is now the Bering Straits (e.g., van Steenis 1962), and yet such groups are now known to have occurred in the Beringian region (van Buseck 1971; Wolfe 1972).

Under conditions of high temperatures and prolonged winter darkness, the predicted vegetation would be broad-leaved deciduous with a minor broad-leaved evergreen element (van Steenis 1962), composed of those evergreens tolerant of low light levels (as a limited number of broad-leaved evergreen taxa are today). This is apparently the type of vegetation that existed in Alaska north of latitude 60°, during the Paleocene.

I am suggesting that the data thus far indicate that, during the middle Eocene, the light conditions at latitude 60° were more favorable to the
growth of broad-leaved evergreens than at present. During the Paleocene, in fact, latitude 57° (but not 60°) supported a diverse broad-leaved evergreen forest. The only factor that could produce more light at these northern latitudes is a significantly smaller (at least 15° less during the middle Eocene than now) inclination of the earth’s rotational axis. A smaller inclination would certainly be consistent with the low mean annual range of temperature during the Paleocene and Eocene: today this temperature parameter is primarily (although not entirely) a function of latitudinal position because of the inclination.

A suggestion that the inclination was, in comparison to today, considerably smaller is, if the obvious warmth of the Alaskan middle Eocene is accepted, contradicted by the Milankovitch calculations, i.e. a smaller inclination would yield lower insolation at high latitudes and hence lower temperatures. These calculations were, however, based on the assumption that the insolational values could be directly translated into temperature values—i.e. that the present atmospheric circulation pattern was, in general, constant throughout geologic time. But we have seen that the Paleocene and Eocene circulation pattern could not have been like that of the present. Could an increased insolational gradient under a low inclination have been the major driving force for a dominantly meridional circulation, a circulation that would have more than compensated for decreased annual insolational values at high latitudes? Perhaps at some critical value of inclination, the atmospheric circulation changes from one that is dominantly cellular (as it is today and was during the Oligocene and Neogene) to one that is dominantly meridional.

If the major climatic trends during the Tertiary were largely the result of inclinational changes, then from the Paleocene to the middle Eocene, inclination decreased gradually from a value of perhaps 10° to a value approaching 5°. The inclination then began to increase slightly until the end of the Eocene, when the inclination increased rapidly to 25–30°. Since then, the inclination has gradually decreased to the present average value of 23.5°.

The drastic change in inclination suggested as the cause of the terminal Eocene event would have had a profound effect on the earth’s crust. It is significant that a number of researchers have suggested major tectonic changes at the end of the Eocene. For example, Molnar et al. (1975) suggest that the tectonic patterns of the South Pacific were different in the pre-Oligocene than now and that the current patterns were achieved at the end of the Eocene. Menard (1978) similarly indicates major changes in the northeastern Pacific at the end of the Eocene.

Yet, even assuming the validity of this model of inclinational change, the several fluctuations in mean annual temperature are not explained. From available radiometric data, the fluctuations appear to represent a cycle about 9.5 m.y. in duration (Wolfe 1971). Presumably such regular fluctuations would result from fluctuations in the amount of solar radiation reaching the earth; certainly no model of plate tectonic movements could explain such fluctuations.

Much additional information is needed, particularly from the continental interiors, to develop accurate models of temperature and precipitation distribution during the Paleocene and Eocene. Low-latitude leaf floras of Oligocene and Neogene age are needed to determine whether the low-latitude data thus far accumulated are anomalous or typical. More studies of modern depositional environments are needed to understand fully the significance of what is actually found in fossil assemblages. More information from rigidly controlled experiments is needed to determine the physiological response of broad-leaved woody plants to low light levels.

This review has shown the type of data that can be obtained from fossil plants. Brooks (1949) noted that the evidence available to him could not be explained solely by geographic factors, and even attempts to explain Paleocene and Eocene climates by the changing positions of the continental plates are only partially satisfactory (Frakes and Kemp 1973). The evidence now available indicates even more radical differences between present climates and those of the past than were recognized by Brooks. Attempting to fit such data into a “steady-state” hypothesis would be doing an injustice to the data similar to that done to geologic data prior to the general acceptance of plate tectonics.

References


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—I don’t know what it measured. The Richter scale is down there.”

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