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1975, pp. 85-88. https://doi.org/10.56577/FFC-26.85

in:

Las Cruces Country, Seager, W. R.; Clemons, R. E.; Callender, J. F.; [eds.], New Mexico Geological Society 26 th Annual Fall Field Conference Guidebook, 376 p. https://doi.org/10.56577/FFC-26

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TERTIARY FLORAS FROM THE RIO GRANDE RIFT

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Several small Tertiary floras from the Rio Grande depression occur in sedimentary rocks associated with volcanic sequences that range from late Eocene (~ 40 m.y.) to middle Miocene (~ 14-15 m.y.). The samples are small, yet they represent very different kinds of vegetation, and must therefore have lived under very different climates. Since three of them lived within a time span of only 6 to 8 m.y., from late Eocene to middle Oligocene, the climatic differences they indicate appear to reflect differences in altitude as well. Their analysis can provide information regarding the topographic history of the Rio Grande rift.

The nature of the floras, as summarized in Figure 1, reveal a progression from a mixed evergreen-deciduous hardwood forest (Bernalillo flora) that lived under warm temperate climate without frost, to vegetation in the transition from broad-leaved sclerophyll to mixed conifer forest (Red Rock Ranch) that suggests mild temperate climate with light frost, to pure subalpine conifer forests (Hermosa and Hillsboro floras) that represent high montane environments of cold temperate climate with regular frost and snow. This shift toward colder climate appears to reflect increasing altitude, presumably broad doming—no doubt complex—that accompanied thermal expansion as volcanism spread over the region commencing in the late Eocene.

The change in altitude that is inferred to account for the progression toward increasingly colder climate can be estimated because different kinds of vegetation replace one another as temperature is lowered with increasing altitude. In this regard, we may recall the changes that occur today as one proceeds up the Rio Grande trough, from desert, through grassland, into juniper woodland, then pirion woodland, ponderosa pine forest, mixed conifer forest, subalpine conifer forest, and finally timberline is reached near 11,000 ft. Mean July temperature in the desert at Socorro is 78°F (25.6°C), but at timberline it is 50°F (10°C).

Flora and Age	Composition	Climate
Tesuque (14-15 m.y., Barstovian mammals).	Palm. Other associates not now known.	Mild temperate, largely frostless.
Hermosa (32 m.y. K/Ar)	Subalpine forest, dominated by high altitude pine. Associates include spruce and few dicot shrubs (*Mahonia*, *Crataegus*) with exceedingly small leaves.	Cold temperate, with much snow and frost.
Hillsboro (32 m.y. K/Ar)	Subalpine conifer forest dominated by fossil bristlecone pine. Associates include only spruce and a *Mahonia* with very small leaflets.	Cold temperate, with regular frost and snow.
Red Rock Ranch (35 m.y., estim.)	Broadleaved sclerophyll vegetation (*Pagopsis*, *Mahonia*, *Rhus*, *Sapindus*) at lower margin of mixed conifer forest (*Picea*, *Pinus*). Most taxa are in Florissant flora (Farkas, 1969).	Mild temperate, with light frosts.
Bernalillo (pollen) (40 m.y., Duchesnean mammal fauna)	Mixed forest of subtropical taxa (*Acalypha*?, *Bombacopsis*, *Morus*, *Palmae*, *Thouinia*) and temperate hardwoods (*Alnus*, *Juglans*?, *Pterocarya*, *Ulmus-Zelkova*) (Leopold and MacGinitie, 1972).	Warm temperate, frostless climate.

Figure 1. Age, composition, and climatic indications of Tertiary floras from the Rio Grande depression.

The attitudinal separation between stations in two different vegetation zones can be estimated by the difference in mean annual temperature, multiplied by lapse rate (Axelrod, 1965, 1968). The basis for the method is clarified by Figure 2 which shows a transect of stations from Galveston, Texas, into central New Mexico. Using Galveston as a datum for sea level, the altitudes of the distant stations were calculated using a lapse rate of 2.8°F. This is close to the thermal terrestrial lapse rate of 3.0°F/1,000 ft which reflects both air and ground temperature as measured at instrument shelter height at meteorological stations. It is lower than the normal standard lapse rate of 3.6°F/1,000 ft which represents the temperature decrease in air free from the surface. The small differences in calculated altitude over the distance of 750 miles into New Mexico re-

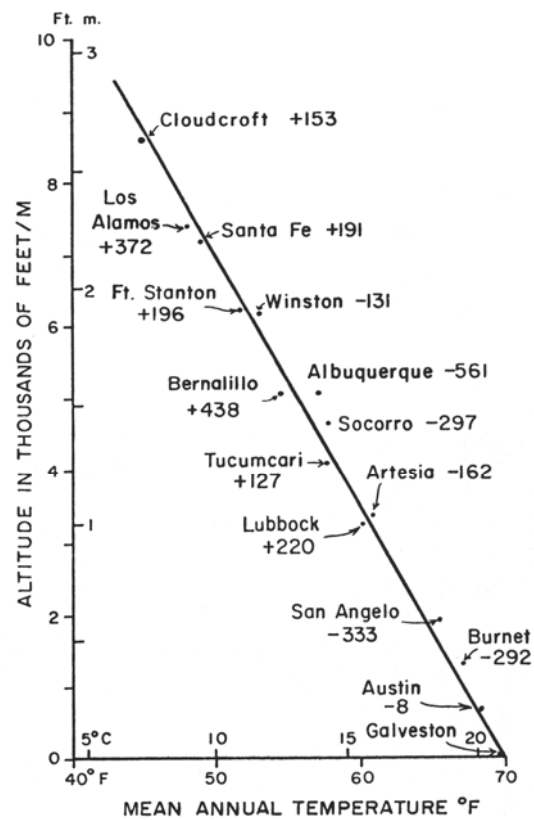

Figure 2. Calculated altitudes of modern stations along the 750-mile transect from Galveston, Texas to the Rio Grande depression, using a thermal terrestrial lapse rate.

flect variation in exposure of stations, temperature inversion (i.e., Albuquerque), cold air drainage, and other factors.

With respect to estimating paleotemperature during the early Tertiary, continents were much lower, high cordilleras had not yet been built up, the continents were bathed by much warmer water in middle and higher latitudes, large ice caps were not yet in existence, and there was only a gentle temperature gradient poleward. As a result, ranges and extremes of temperature were greatly damped as compared with those of today. Hence, any estimates of altitude from inferred paleotemperatures should be no less accurate than those of today (Fig. 2). Assuming an adequate sample, the chief source of error lies in determining mean annual temperature *(T).* Errors can be reduced by plotting temperatures of meteorological stations in vegetation zones similar to fossil floras on a Bailey nomogram, shown here in Figure 3 (Bailey, 1960, 1964). Charting the thermal parameters of vegetation (Axelrod, 1965, 1968) allied to fossil floras makes it possible to compare visually the warmth of climate (W), the temperateness of climate *(M),* and frost frequency of vegetation allied to fossil floras. Comparisons are strengthened because the nomogram also sets out timberline (W 50), the lower margin of subalpine forest (W 53), the margin of wet tropical forest (W 62.5), and other critical biotherms. By balancing thermal parameters implied by the vegetation a fossil flora represents, the reliability and consistency of estimates of both mean annual temperature *(T)* and the range of temperature *(A)* are improved, as is the estimate of paleotemperature.

The estimates of temperature for fossil floras from the Rio Grande depression are shown in Figure 4, column A. Present temperatures at stations from Galveston into New Mexico are in Column B for comparison. Temperatures inferred for the late Eocene Jackson and Fayette floras from south-central Texas (Berry, 1924; Ball, 1931, 1939), and the small Oligocene Catahoula flora in Texas-Louisiana-Mississippi (Berry, 1916), provide a datum for estimating altitude from sea level. Note again there was a lower range of temperature *(A)* during Eocene-Oligocene time, which expresses the greater temperateness of those climates. The range of temperature *(A* 20) selected for the fossil series is based on the opinion that the Bernalillo flora indicates essentially a frost-free climate, though not tropical as stated by Leopold and MacGinitie (1972). Its position close to the line 0.1 percent of the hours of the year with freezing (Fig. 3) is thus near the *extreme* condition under which it may have lived. The mean annual temperature *(T)* selected for the late Eocene floras of the Gulf Coast does not differ appreciably from that in the area today

70°F). However, climate was warmer than at present because the range of temperature *(A)* was lower. As shown on the nomogram (Fig. 3), for any station with a mean annual temperature greater than 58°F, a decrease in the range of temperature *(A)* increases the warmth of climate (W). Today, temperatures at Galveston are *T* 70° and *A* 30°, giving the area a warmth of W 61.3°F, or 253 days with a mean temperature above that level. But with the postulated mean temperature of 70°F and range of temperature of 16°F, warmth of climate is increased to W 63.3°F, or 300 days with mean temperature warmer than 63.3°F. Under conditions of ample, well-distrib-

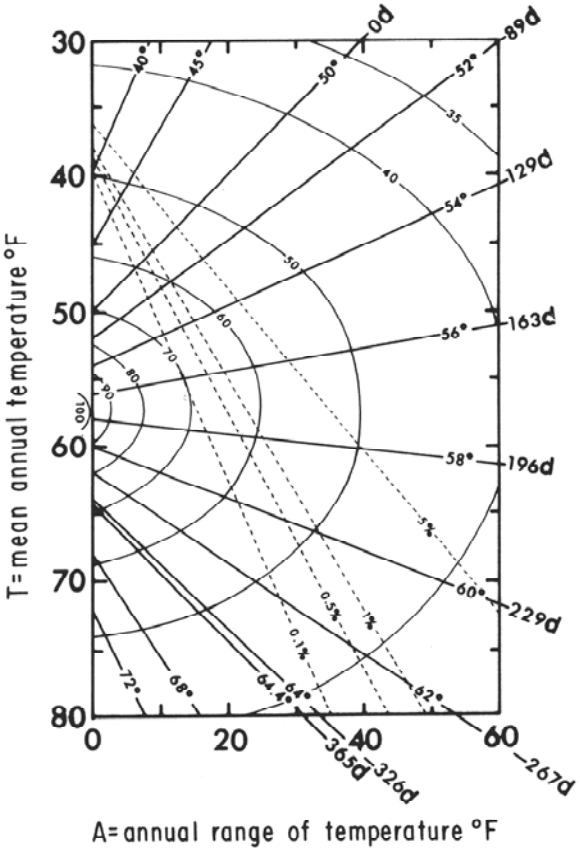

Figure 3. Nomogram by H. P. Bailey showing warmth and temperateness of climate. (See footnote to Figure 5).

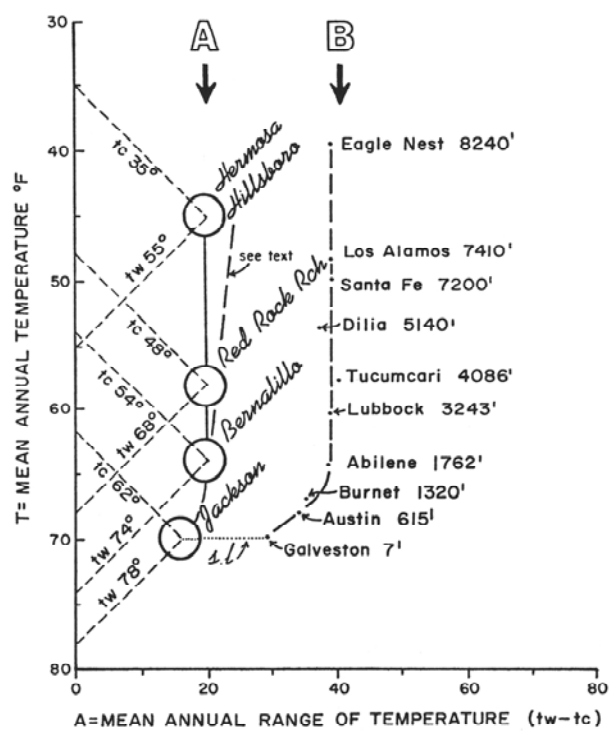

Figure 4. Estimated temperatures of fossil floras from the Gulf Embayment to the Rio Grande axis in Eo-Oligocene time (column A), compared with temperatures at stations along the same transect today (column B).

uted rainfall, this would be more than suitable for tropical rainforest.

The diagonal lines diverging to the left from each "circle of confidence" are temperatures of the warmest *(tw)* and coldest *(tc)* months, or those of January and July, assuming a normal temperature distribution. The inferred temperatures for the fossil floras, and the altitudes they appear to indicate, are presented in Figure 5. The data seem to be consistent. If mean temperature at sea level is increased significantly, altitudes increase quickly to levels that become questionable. For instance, if the mean temperature *(T)* of the Jackson flora is raised to 75°F (23.9°C), then the altitude of timberline, marked by radian W 50°, is 33° of mean annual temperature *(T)* higher. Assuming a terrestrial lapse rate of 3.0°F/1,000 ft, this places late Eocene timberline at 10,600 ft (3,200 m). This is the general altitude of timberline in the area today, when the range of temperature *(A)* is fully 18°F greater! Clearly, an estimate of 70°F mean annual temperature is more consistent with the evidence as now known.

Estimation of the increase in range of temperature *(A)* that may have occurred during the span from about 40 to 32 m.y. must await the discovery of new floras. In this regard, a moderate increase in annual range *(A),* and hence a decrease in winter temperature, is implied by the dashed line in Column A that leads to *A* 24°F (Fig. 4). This would not affect the estimates of altitude because annual temperature is unchanged. However, the mean July and January temperature for Hermosa-Hillsboro floras would shift from 55° to 57°F and from 35° to 33°F, respectively (Fig. 5). Such a change, from 10 percent to about 12 percent of the hours of the year with temperatures below freezing, is sufficiently close to a mean January temperature of 32°F to suggest that it could have altered sufficiently the high montane flora present earlier (pre-32 m.y.) to account for the highly impoverished Oligocene forests at Hermosa and Hillsboro.

CONCLUSION

The sequence of small floras from the Rio Grande depression reflects a progressive change in vegetation from the upper margin of mixed evergreen-deciduous hardwood forest (Bernalillo) to subalpine conifer forest (Hillsboro and Hermosa floras). This implies an estimated minimum decrease in mean annual temperature of about 18°F (10°C). This seems related to an increase in altitude of at least 6,000 feet (18° x terrestrial lapse rate 333 ft/1°F) in 6 to 8 m.y. (Fig. 6), and is presumed to reflect broad arching that accompanied volcanism. Uplift may have been greater because the Hermosa and Hillsboro floras appear to lie on the flank of a volcano, not on the crest of the arch which may have averaged 2,000 ft higher.

The occurrence of palm in the Tesuque Formation near Santa Fe indicates essentially frontless climate in the Rio Grande trough during late Miocene (14 to 15 m.y.). This provides a marked contrast with the Oligocene Hermosa and Hillsboro subalpine conifer floras that indicate cold, snowy winters, and are now at comparable altitudes to the south. Their present position in the juniper and pirion belts, fully 3,000 and 4,000 ft below subalpine conifer forest in the nearby mountains, emphasizes the magnitude of structural change in the region following collapse and trough-formation during the early Miocene and later (Elston and others, 1973).

ACKNOWLEDGMENTS

Research on these floras has been supported by grants from National Science Foundation, to whom thanks are extended. Prof. Harry P. Bailey has critically read the manuscript, and made several suggestions that have materially improved it.

Temperature and Altitude	Jackson F°	Jackson C°	Bernalillo F°	Bernalillo C°	Red Rock F°	Red Rock Ranch C°	Hermosa & Hillsboro F°	Hermosa & Hillsboro C°
Mean annual temperature (T)	70°	21.1°	64°	17.8°	58°	14.5°	45°	7.2°
Mean range of temperature (A)	16	9	20	11.2	20	11.2	20	11.2
Mean temp. warmest month (tw)	78	25.6	74	23.4	68	20	55	12.8
Mean temp. coldest month (tc)	62	16.7	54	12.3	48	8.9	35	1.7
Warmth of climate (W), and	63.3	17.4	59.6	15.3	57.5	14.2	52	11.1
no. of days* (d)	300 d	300 d	222 d	222 d	187 d	187 d	89 d	89 d
% hrs of year with frost	0		0.1		0.5		12	
Estimated altitude (ft)	0		2000		4000		8300	
Estimated altitude (m)	0		600		900		2500	

*Days with mean temperature above the stipulated W. The lines of warmth (W), represented by radians on the nomogram (Fig. 2), correspond to growing seasons of decreasing length and temperature poleward, or with increased altitude. At W 50°F there are 0 days warmer than 50°F, at W 64.4°F there are 365 days with mean temperature above 64.4°F (see Bailey, 1960).

Figure 5. Estimated temperature conditions and altitudes of fossil floras from the Gulf Embayment to the Rio Grande axis.

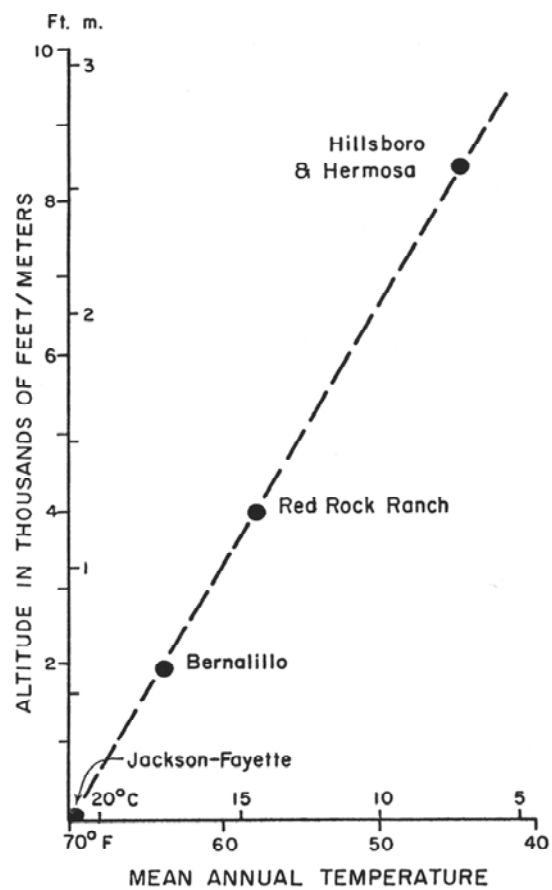

Figure 6. Estimated altitudes of fossil floras from the Gulf Embayment to the Rio Grande axis in Eo-Oligocene time.

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