[AMERICAN JOURNAL OF SCIENCE, VOL. 294, MAY, 1994, P. 621–640]

STABLE OXYGEN AND CARBON ISOTOPES OF PEDOGENIC CARBONATE AS INDICATORS OF PLIO-PLEISTOCENE PALEOCLIMATE IN THE SOUTHERN RIO GRANDE RIFT, SOUTH-CENTRAL NEW MEXICO

GREG H. MACK,* DAVID R. COLE,** W. CALVIN JAMES,***
THOMAS H. GIORDANO,* AND STEPHEN L. SALYARDS****

ABSTRACT. Stable oxygen and carbon isotopes of pedogenic carbonate provide a detailed record of paleoclimatic changes from late Pliocene through early Pleistocene in the Rio Grande rift of south-central New Mexico. A total of 30 calcic paleosols were sampled at three stratigraphic sections of the fluvial lithofacies of the Camp Rice Formation, and one calcic paleosol was sampled from fluvial sediment inset against the Camp Rice Formation. Paleosols commonly consist of an argillic B horizon (Bt) overlying a calcic (Bk) or petrocalcic (Km) horizon. The majority of paleosols consist of stage II morphology calcic horizons, although one stage V horizon and five stage III horizons were also sampled. Reversal magnetostratigraphy at all four sample sites bracket the age of the paleosol-bearing strata between 3.4 and 0.7 Ma and allow estimates of the absolute age of individual paleosols.

Three paleoclimatic stages are indicated by the carbon and oxygen isotopic data from south-central New Mexico. The initial stage, from 3.1 to 2.5 Ma, was characterized by the overall lowest values of ∂^{18}O and ∂^{13}C and by an increase in values with decreasing age, suggesting high effective moisture and abundant winter precipitation, which decreased through time, and/or relatively low temperature, which increased through time. The second stage (2.5-1.4 Ma) displays an increase in ∂^{18}O with decreasing age but no significant change in ∂^{13}C with time, suggesting that the effective moisture was nearly constant, but that temperature and/or summer precipitation may have increased through time. The final stage (1.4-0.7 Ma) shows an overall increase in both ∂^{18}O and ∂^{13}C with decreasing age corresponding to less effective moisture, higher temperature, and/or greater summer precipitation through time. Plio-Pleistocene paleoclimatic changes in south-central New Mexico correlate well with paleoclimatic data elsewhere in the southwestern United States and adjacent Great Plains and may have been influenced by the onset of Northern Hemisphere continental glaciation, rise of the Sierra Nevada and Transverse Ranges, and/or broad regional uplift of the western United States.

INTRODUCTION

Recent speculations concerning future climatic changes have led to renewed interest in the interpretation of late Tertiary and Quaternary

---

* Department of Geological Sciences, New Mexico State University, Las Cruces, New Mexico 88003

** Chemistry Division, Oak Ridge National Laboratory, Building 4500 S, Oak Ridge, Tennessee 37831

*** Department of Geological Sciences, Ohio State University, Columbus, Ohio 43210

**** Department of Earth and Space Sciences, University of California, Los Angeles, Los Angeles, California 90024 paleoclimate. The ability to predict accurately future climate depends not only on an understanding of modern climate but knowledge of climate in the recent geological past as well. Calcic paleosols in the late Pliocene to early Pleistocene Camp Rice Formation of south-central New Mexico provide a detailed record of terrestrial paleoclimatic change over the period from 3.1 to 0.7 Ma. The paleosols are present in numerous outcrops of the formation and are subequally distributed within the stratigraphic sections. High-resolution reversal magnetostratigraphy is available for the same stratigraphic sections that contain the paleosols (Mack, Salyards, and James, 1993).

Although the presence of calcic paleosols is itself an indicator of relatively dry paleoclimate, small-scale fluctuations in temperature and/or precipitation can be determined by the stable oxygen and carbon isotopic composition of pedogenic carbonate. In his study of modern calcic soils, Cerling (1984) demonstrated that $\partial^{18}O$ of pedogenic carbonate is related to the oxygen isotopic composition of the ambient meteoric water from which the carbonate precipitated, which in turn is affected by mean annual temperature, seasonality of precipitation, and isotopic enrichment during evaporation. Cerling (1984) and Quade, Cerling, and Bowman (1989) further showed that the carbon isotopic composition of pedogenic carbonate is related to the relative abundance of C_4, C_3, and CAM plants growing on the soil. C_4 grasses and CAM plants provide relatively heavy carbon isotopes to the soil environment, both through oxidation of plant material and respiration, and are adapted to high water stress and high temperature. Also important is the relative abundance of vegetative ground cover. Sparse vegetation allows movement into the soil of atmospheric CO_2, which has a higher $\partial^{13}C$ value than C_4 grasses and CAM plants. These relationships have been applied as a paleoclimatic indicator to rocks ranging in age from Permian to Quaternary (Cerling, Hay, and O'Neil, 1977; Cerling and Hay, 1986; Suchecki, Hubert, and Birney De Wet, 1988; Gregory and others, 1989; Naylor and others, 1989; Cerling and Quade, 1990; Mack and others, 1991; Wang and others, 1993; Smith and others, 1993). The isotopic data presented in this study provide a more complete record of pre-middle Pleistocene paleoclimate in southern New Mexico than has been accomplished by other paleoclimatic techniques.

STRATIGRAPHIC SETTING

The Camp Rice Formation was deposited during the most recent phase of extension in the southern Rio Grande rift (Seager and others, 1984; Mack and Seager, 1990). The Camp Rice Formation ranges in thickness from 20 to 130 m and is subdivided into piedmont and axial-fluvial lithofacies (fig. 1; Mack and Seager, 1990). The axial-fluvial lithofacies sampled in this study was deposited by the south-flowing Ancestral Rio Grande, which ultimately emptied into lakes in west Texas and Chihuahua, Mexico (Kottlowski, 1953; Reeves, 1965, 1969; Strain, 1966; Hawley and others, 1969). Fluvial channel deposits are composed of pebbly medium sand/sandstone, whereas floodplain strata consist of

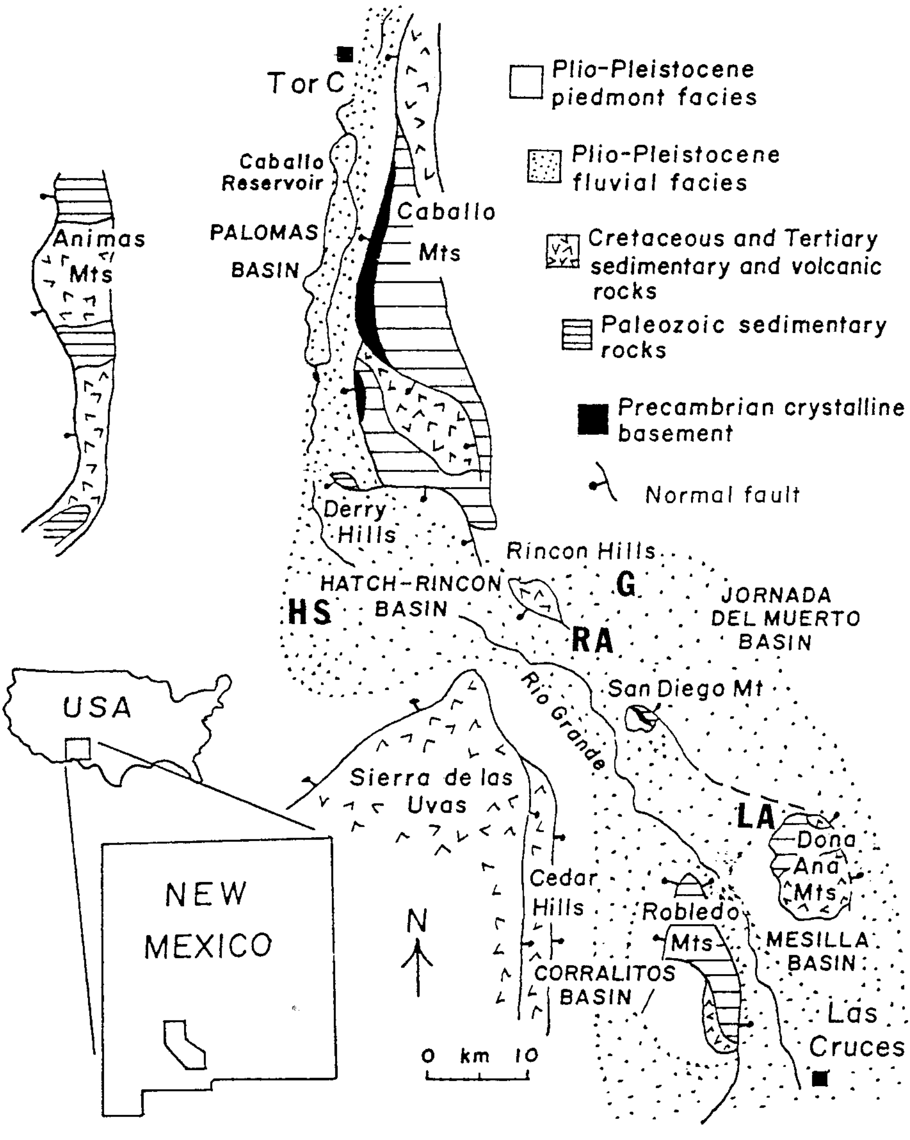

Fig. 1. Index map of the Rio Grande rift in south-central New Mexico, showing location of sample sites within the Camp Rice Formation and the sample site at Grama, which is inset against the Camp Rice Formation. HS = Hatch Siphon; RA = Rincon Arroyo; LA = Lucero Arroyo; G = Grama.

mudstone and silt to fine sand (Mack and Seager, 1990). Deposition of the Camp Rice ended when the Ancestral Rio Grande began to entrench the basins, as a result of capture by the lower Rio Grande, tectonism, and/or climate change (Hawley and Kottlowski, 1969; Hawley, 1981).

The constructional top of the formation known as the lower La Mesa surface above fluvial strata is considered to be an approximate time line (Mack, Salyards, and James, 1993).

The age of the Camp Rice Formation and coeval Palomas Formation north of the study area has been bracketed between late Pliocene and early Pleistocene by a combination of (1) radiometric dates of basalt flows that underlie, overlie, and are interbedded with the formations (Bachman and Mehnert, 1978; Seager and others, 1984), (2) tephrochronology of fallout ash beds within and inset against the formations (Reynolds and Larsen, 1972; Izett and others, 1981; Kortemeier, 1982; Lozinsky and Hawley, 1986a,b), (3) a Blancan and Irvingtonian vertebrate fauna (Strain, 1966; Hawley and others, 1969; Tedford, 1981; Lucas and Oakes, 1986; Repenning and May, 1986; Vanderhill, 1986), and (4) reversal magnetostratigraphy (Vanderhill, 1986; Mack, Salyards, and James, 1993).

The stratigraphic sections sampled in this study are dated and correlated using reversal magnetostratigraphy of Mack, Salyards, and James (1993). All three Camp Rice sections (Rincon Arroyo, Hatch Siphon, Lucero Arroyo) have the constructional top (La Mesa geomorphic surface), whereas the base of the Camp Rice Formation is exposed only at Hatch Siphon and Lucero Arroyo (figs. 2, 3, 4). Hatch Siphon contains a nearly complete Gauss section with both the Kaena and Mammoth subchrons represented. The section at Rincon Arroyo also has a thick Gauss section, but only one subchron is represented, which is interpreted, because of its position low in the profile, to represent the Mammoth. The Gauss section at Lucero Arroyo is much thinner than at the other two sections and is interpreted to represent the interval between the Kaena subchron and the Gauss-Matuyama boundary. Alternatively, the section at Lucero Arroyo could represent a condensed section of the entire Gauss with both subchrons missing. However, relatively rapid sediment accumulation rate, suggested by the presence of fluvial channel deposits and relatively immature stage II calcic paleosols, suggests that the Lucero Arroyo Gauss section is not condensed, and the close paleomagnetic sampling makes it unlikely that a reversed interval was missed (Mack, Salyards, and James, 1993).

The most complete Matuyama section is at Rincon Arroyo, which displays all four normal subchrons (fig. 2). Magnetostratigraphy of the Rincon Arroyo section is strengthened by the presence of a pumice-clast conglomerate derived from either the Cerro Toledo eruptions (1.23-1.47 Ma; Izett and others, 1981) or from the early Bandelier Tuff eruption (1.5 Ma; Spell, Harrison, and Wolff, 1990) in the Jemez volcanic field of northern New Mexico. Regardless of which event it represents, the pumice-clast conglomerate occupies a position between the Olduvai and Jaramillo subchrons.

The Matuyama intervals at Hatch Siphon and Lucero Arroyo are condensed compared to Rincon Arroyo. The paucity of channel deposits at Hatch Siphon, their absence at Lucero Arroyo, and the presence of

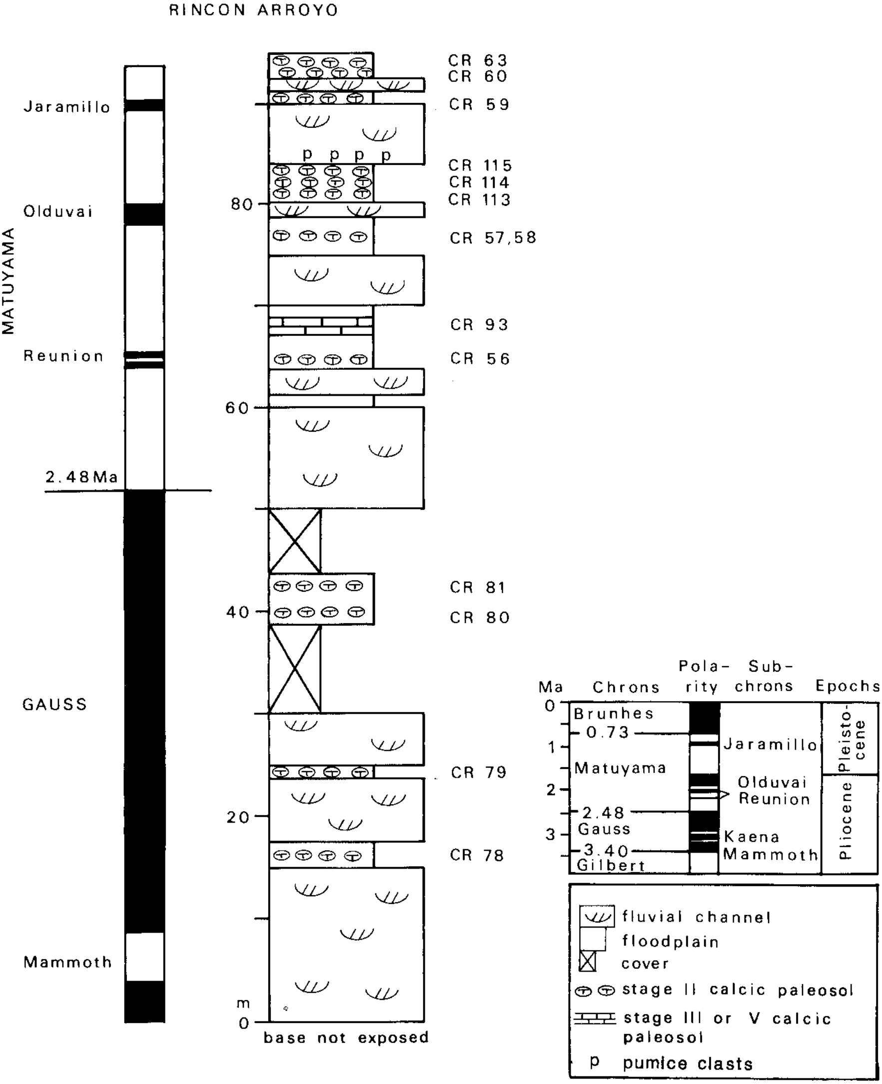

Fig. 2. Stratigraphic section of the Camp Rice Formation at Rincon Arroyo. CR numbers refer to sample sites of pedogenic carbonate. Polarity reversal stratigraphy is based on Mack, Salyards, and James (1993).

mature stage III and V calcic paleosols at both sections support the interpretation that deposition during Matuyama time at Hatch Siphon and Lucero Arroyo was intermittent and was separated by long periods of nondeposition and pedogenesis (Mack and James, 1992; Mack, Salyards, and James, 1993). No attempt has been made to correlate the normal subchron near the top of the Lucero Arroyo section.

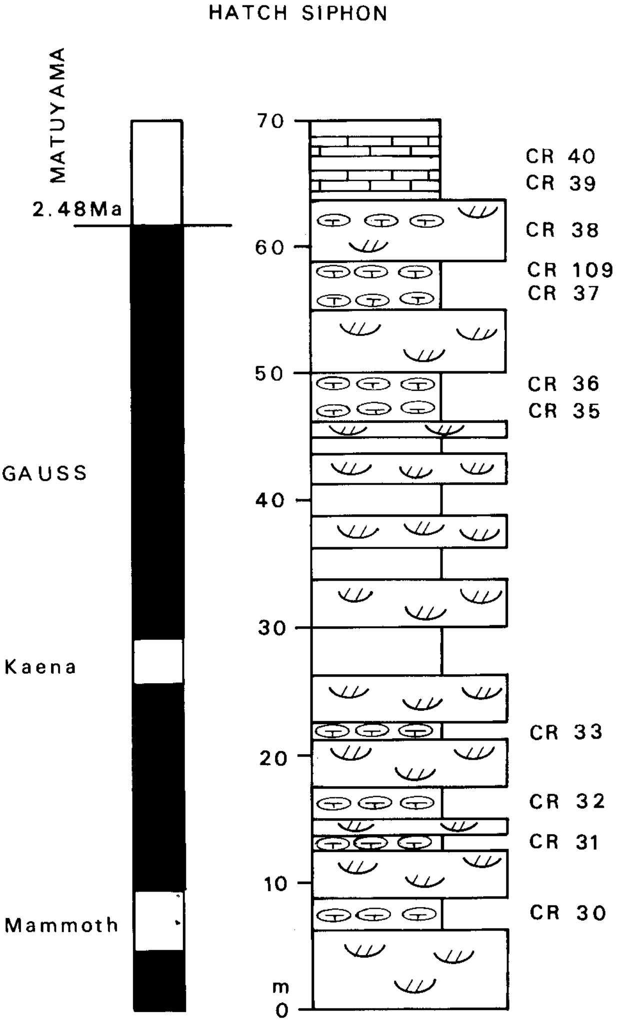

Fig. 3. Stratigraphic section of the Camp Rice Formation at Hatch Siphon. See figure 2 for description of symbols.

A paleosol at Grama was also sampled as part of this study. Strata at Grama occupy an inset surface and thus post-date Camp Rice deposition (Mack, Salyards, and James, 1993). The Grama section straddles the Matuyama-Brunhes boundary, an interpretation supported by the presence within the section of the Bishop ash (fig. 4; Seager and Hawley, 1973; Kortemeier, 1982). Because of its proximity to the Rincon Arroyo section, the Grama data point is included with the Rincon Arroyo data set.

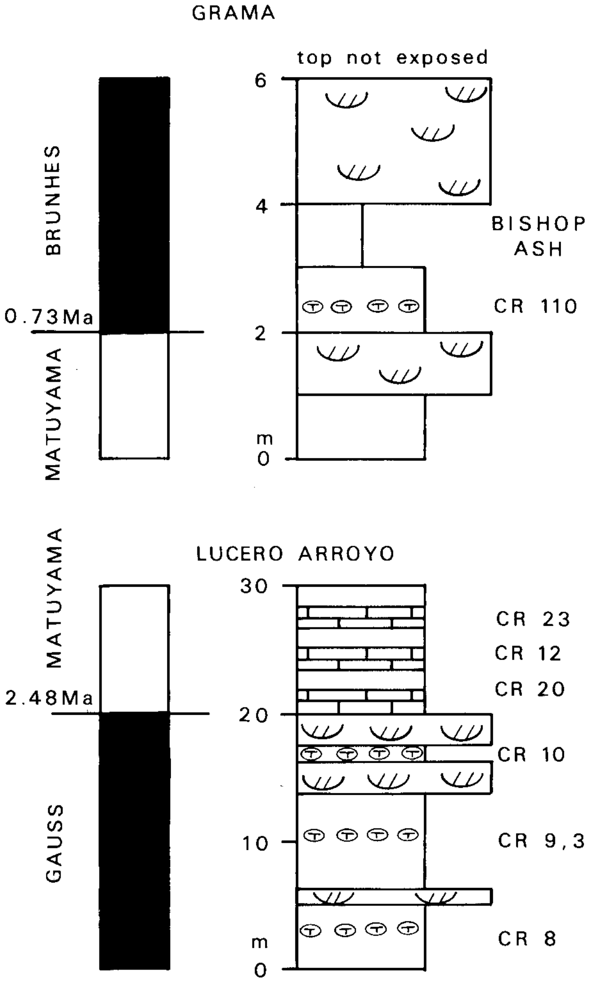

Fig. 4. Stratigraphic section of the Camp Rice Formation at Lucero Arroyo and a section of sediment inset against the Camp Rice Formation at Grama. See figure 2 for description of symbols.

DESCRIPTION OF PALEOSOLS

Calcic paleosols in the Camp Rice Formation are described by Mack and James (1992) and will be summarized here. The best developed paleosol profiles consist of an argillic B or structural B horizon overlying calcic or petrocalcic horizons. A horizons are very rare, because of truncation of the upper part of the paleosol profiles.

Argillic B horizons (Bt) are present in both mudstone and silt-sand parent sediment and range in thickness from 8 to 100 cm, with the lowest values underlying truncation surfaces. Common features of argillic B horizons are blocky or prismatic peds, root traces, some of which are calcareous, and slickensides. In a few cases the argillic B horizon is mottled brown and green, indicating gley conditions. Diagnostic of argillic B horizons is the presence of clay coats (argillans) around detrital grains and peds or lining skew planes and vughs. The morphology of the argillans and down-profile increase in the percentage of argillans suggest that they represent translocated clay (Mack and James, 1992). Structural B horizons (Bw) are similar in thickness and morphology to argillic B horizons but lack argillans.

Gradationally underlying argillic and structural B horizons are calcic (Bk) and petrocalcic (Km) horizons. Calcic B horizons range in thickness from 20 to 140 cm and are present in both mudstone and silt-sand parent sediment. The diagnostic features of calcic B horizons are 2 to 15 cm diameter nodules and tubules of microcrystalline low-Mg calcite. Many tubules are elongate perpendicular to bedding and taper downward, suggesting an origin as rhizoliths (Klappa, 1980). Nodules and tubules are randomly scattered throughout the horizon and are separated by parent sediment, a morphology corresponding to stage II of Gile, Peterson, and Grossman (1966), Bachman and Machette (1977), and Machette (1985). The parent sediment commonly displays blocky peds, slickensides, and argillans. Locally, the calcic B horizon is the only horizon present, as a result of truncation of the upper part of the profile.

Also underlying argillic B horizons are thick (50–250 cm), strongly indurated horizons which contain over 90 percent microcrystalline low-Mg calcite. These horizons qualify as both petrocalcic and Km horizons (Gile, Peterson, and Grossman, 1965). All but one of the Km horizons correspond to stage III morphology of Gile, Peterson, and Grossman (1966), Bachman and Machette (1977), and Machette (1985). The exception, corresponding to sample CR 12 at Lucero Arroyo, has a 5-cm-thick laminar and pisolithic cap above the massive carbonate and represents stage V of Bachman and Machette (1977) and Machette (1985). Soils with Km horizons also developed on the constructional top of the Camp Rice Formation (La Mesa surface) but were not sampled as part of this study.

METHODS

Sampling.—Calcic paleosols were sampled at three stratigraphic sections of the Camp Rice Formation (Hatch Siphon, Rincon Arroyo, Lucero Arroyo) and one section inset beneath the top of the Camp Rice Formation (Grama; fig. 1). All the sections consist of axial-fluvial lithofacies. The samples are restricted to calcic nodules rather than rhizoliths, in order to reduce possible local effects of root respiration or decomposition on carbon isotopic composition of the pedogenic carbonate. Samples of pedogenic carbonate were taken in the lower part of calcic and petrocalcic horizons in order to reduce the influence of down-profile changes in isotopic composition demonstrated in modern soils by Quade, Cerling, and Bowman (1989). It is not always possible, however, to determine the exact position of the sample within the paleosol profile because of truncation of the paleosol prior to burial.

In order to evaluate the role of diagenesis, all the samples in this study were examined in thin section. Diagenetic modification is considered negligible because of: (1) lack of evidence of recrystallization of pedogenic micrite, (2) paucity of spar cement and spar-filled veins, (3) burial depths did not exceed the thickness of overlying Camp Rice strata (< 100 m), and (4) lack of evidence of geothermal activity at the sample sites.

The assignment of a specific age to a paleosol in table 1 and figures 5 and 6 is based on the position of the paleosol with respect to chron and subchron boundaries bracketing the paleosol. The age of each paleosol was calculated by: (1) determining the stratigraphic distance of the paleosol above or below one of the chron/subchron brackets, (2) dividing

TABLE 1

Interpolated age and isotopic composition of pedogenic carbonate of the Camp Rice Formation. All paleosols are stage II morphology unless otherwise stated

Section/Sample	Age (Ma)	$\partial^{18}O_{PDB}$	$\partial^{13}C_{PDB}$	Comments
Rincon Arroyo				
CR 78	2.96	−10.6	−4.8	
CR 79	2.85	−10.8	−4.6	
CR 80	2.66	−10.1	−3.7	
CR 81	2.62	−10.0	−4.1	
CR 56	2.13	−8.5	−4.1	
CR 93	2.02	−8.3	−2.6	av. 3, depth; stage III
CR 58, 57	1.88	−8.8	−4.2	av. 3, depth, core/rim
CR 113	1.53	−8.3	−4.0	av. 2, core/rim
CR 114	1.39	−8.8	−3.6	
CR 115	1.22	−7.7	−3.2	av. 2, core/rim
CR 59	0.89	−8.3	−2.7	
CR 60	0.85	−6.6	−3.9	
CR 63	0.84	−7.2	−3.7	
Grama				
CR 110	0.73	−6.9	−2.0	av. 2, duplicate
Hatch Siphon				
CR 30	3.10	−8.2	−5.5	
CR 31	3.04	−9.5	−4.6	
CR 32	3.03	−9.2	−5.3	
CR 33	3.02	−9.0	−4.8	
CR 35	2.70	−8.8	−2.4	
CR 36	2.66	−8.1	−3.0	
CR 37	2.56	−8.6	−3.3	
CR 109	2.52	−8.7	−2.5	
CR 38	2.48	−7.7	−3.7	
CR 39	1.85	−7.1	−3.5	stage III
CR 40	1.54	−6.8	−4.1	av. 4, depth, along strike; stage III
Lucero Arroyo				
CR 8	2.84	−8.9	−3.5	av. 2, duplicate
CR 9,3	2.65	−9.2	−3.3	av.2, along strike
CR 10	2.56	−9.2	−4.0	av. 2, duplicate
CR 20	2.32	−6.0	−3.9	stage III
CR 12	2.00	−6.5	−4.1	av. 4, depth; stage V
CR 23	1.48	−6.0	−4.7	av. 3, depth; stage III

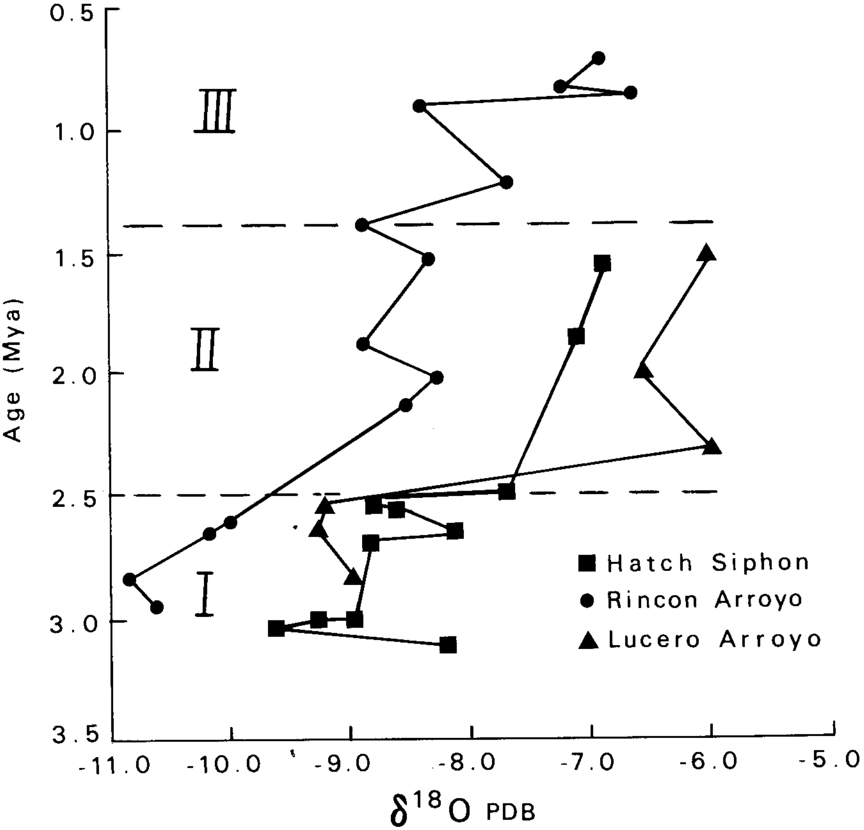

Fig. 5. Bivariate plot of age versus $\partial^{18}O_{PDB}$ of pedogenic carbonate of the Camp Rice Formation. Grama data point is plotted with the Rincon Arroyo data points. Roman numerals refer to paleoclimatic stages discussed in text.

the stratigraphic distance from the selected boundary by the sediment accumulation rate of the strata between the chron/subchron brackets, and (3) adding or subtracting the resultant time value to the age of the chron/subchron from which the stratigraphic difference was determined. In the case of the Hatch Siphon section, the age of the base of the section was considered to correspond to the Gauss-Gilbert boundary. The age of the constructional top of the Camp Rice Formation was considered to be the Matuyama-Brunhes boundary. Age values for the chron/subchron boundaries are taken from Mankinen and Dalrymple (1979).

Isotopic analysis.—Stable isotope measurements were carried out by converting fine-grained micritic calcite to CO_2 liberated by reacting bulk

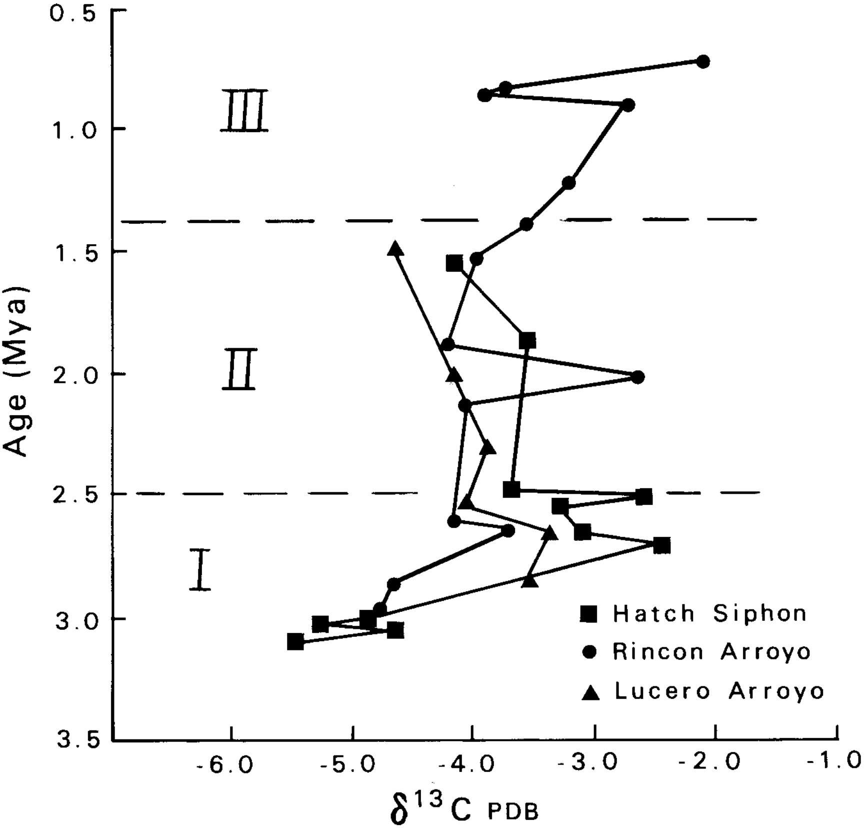

Fig. 6. Bivariate plot of age versus $\partial^{13}C_{PDB}$ of pedogenic carbonate of the Camp Rice Formation. Grama data point is plotted with the Rincon Arroyo data points. Roman numerals refer to paleoclimatic stages discussed in text.

paleosol samples with 100 percent phosphoric acid (McCrea, 1950). Results are reported in the ∂ (permil) notation where,

$$\partial \text{ (permil)} = [(R_{sample}/R_{standard}) - 1]\ 1000,$$

and R_{sample} and $R_{standard}$ refer to the $^{13}C/^{12}C$ or $^{18}O/^{16}O$ ratio in a sample and standard, respectively. The ∂ values are generally reproducible to ±0.1 permil for carbon and ±0.2 permil for oxygen. The calcite $\partial^{13}C$ and $\partial^{18}O$ data, relative to the PDB standard, are presented in table 1 and figures 5 and 6.

To evaluate possible variations in the isotopic data, several tests were performed, including duplicate runs of three samples, core and rim analysis of three samples, sampling two paleosols at locations greater

TABLE 2

Multiple analyses of carbon and oxygen isotopes of pedogenic carbonate of the Camp Rice Formation

Duplicate runs of single sample	$\partial^{18}O_{PDB}$	$\partial^{13}C_{PDB}$
CR 110a	−6.9	−2.0
CR 110b	−6.9	−2.0
CR 8a	−8.9	−3.5
CR 8b	−8.9	−3.5
CR 10a	−9.2	−4.0
CR 10b	−9.2	−4.0
Core and rim of single sample		
CR 57 rim	−9.0	−4.4
CR 57 core	−8.8	−4.2
CR 113 rim	−8.4	−4.0
CR 113 core	−8.2	−4.0
CR 115 rim	−7.6	−3.1
CR 115 core	−7.6	−3.2
Along strike sampling (≥ 1 km)		
CR 3	−9.1	−3.4
CR 9	−9.4	−3.3
CR 40	−6.7	−4.4
CR 40-1	−7.2	−3.3
Depth in profile (cm below top)		
CR 58 (30 cm)	−8.7	−4.1
CR 57 (90 cm)	−8.9	−4.3
CR 12a (65cm)	−6.7	−4.3
CR 126 (80 cm)	−6.4	−4.0
CR 12c (100 cm)	−6.5	−4.0
CR 12d (125 cm)	−6.5	−4.3
CR 23a (65 cm)	−5.8	−4.6
CR 23b (75 cm)	−5.6	−4.5
CR 23c (95 cm)	−6.5	−4.9
CR 40a (35 cm)	−6.7	−4.4
CR 40b (40 cm)	−6.8	−4.3
CR 40c (60 cm)	−6.7	−4.5
CR 93a (160 cm)	−8.6	−3.5
CR 93c (190 cm)	−8.3	−2.2
CR 93d (210 cm)	−8.0	−2.1

than a kilometer apart, and sampling five paleosols as a function of depth in the profile. The results of these multiple analyses are shown in table 2. For those paleosols with multiple analyses, the value listed in table 1 and shown in figures 5 and 6 represents the average of the multiple analyses. In all but three cases, the variation in the multiple analyses is less than 0.5 permil for both carbon and oxygen. The exceptions (CR-93, CR-40, CR-23) display a range of 0.5 to 1.4 permil. All three of these exceptions are stage III calcic paleosols, suggesting that the most mature paleosols may be the least reliable as paleoclimate indicators, because of the long time periods necessary for their formation.

PALEOCLIMATE INTERPRETATION

Isotopic values from lowest to highest stratigraphic position in the Camp Rice Formation range from −6 to −2 permil for $\partial^{13}C$ and −11 to −6 permil for $\partial^{18}O$. The magnitude of the ranges is comparable to those observed in Plio-Pleistocene pedogenic carbonate of Olduvai Gorge by Cerling and Hay (1986) and in southeastern Arizona by Wang and others (1993) and Smith and others (1993), who considered the stratigraphic variability to reflect paleoclimate change. The stratigraphic variation in isotopic composition in the Camp Rice Formation is probably not an artifact of the analytical process, nor does it reflect differences in parent sediment or elevation of the depositional sites. The average difference for duplicate runs of single samples, core and rim analysis of single samples, and analyses of samples from different depth in a profile is one order of magnitude less than the range shown on figures 5 and 6 (table 2). Furthermore, there is no evidence of stratigraphic variation in the detrital composition of the parent sediment of the paleosols. All the paleosols sampled in this study are developed within floodplain strata containing little or no detrital carbonate component. There also is little evidence that differences in elevation are responsible for the isotopic trends. Quade, Cerling, and Bowman (1989) demonstrated that the oxygen and carbon isotopic composition of pedogenic carbonate decreases with increasing elevation by about 4 to 5 permil per 1000 m. Because of relatively low gradients of the modern Rio Grande and by analogy the Ancestral Rio Grande, differences in elevation of the stratigraphic sections at the time of Camp Rice deposition were probably no more than a few meters. Moreover, it seems unlikely that during Camp Rice deposition the basin subsided by 0.5 to 1 km (Seager and others, 1984), which is the amount that would be necessary to account for the observed range in isotopic values by elevation change alone.

We have divided the isotopic data from the Camp Rice Formation into three stages (figs. 5 and 6). The oldest stage is from 3.1 to 2.5 Ma and is best represented by the Hatch Siphon and Rincon Arroyo sections. This interval is characterized by (1) the lowest overall values of $\partial^{13}C$ and $\partial^{18}O$ in the data set, (2) a pronounced increase in $\partial^{13}C$ with decreasing age, and (3) a less pronounced increase in $\partial^{18}O$ with decreasing age. The overall low values of $\partial^{13}C$ indicate a high ratio of C_3 plants/C_4 grasses plus CAM plants and/or a low contribution of atmospheric CO_2 as a result of extensive vegetative ground cover (Cerling, 1984; Quade, Cerling, and Bowman, 1989). These conditions suggest high effective moisture, although progressively decreasing through time. The low values of $\partial^{18}O$ indicate relatively low temperature compared to subsequent time intervals and/or a relatively large component of winter precipitation, which also decreased through time (Cerling, 1984; Wang and others, 1993; Smith and others, 1993).

The second stage is from 2.5 to 1.4 Ma and is well represented by all three stratigraphic sections (figs. 5 and 6). Carbon isotopes display little stratigraphic variation, suggesting near uniform conditions of effective moisture throughout the interval. The anomalous data point at Rincon Arroyo (CR-93) is the only stage III morphology calcic paleosol in the section. Such a mature paleosol requires tens to hundreds of thousands of years to develop (Gile, Hawley, and Grossman, 1981) and as a consequence may have formed over a wide range of climatic regimes. Oxygen isotopes in the second stage show an overall increase with decreasing age and a significant jump across the lower boundary of the stage. The oxygen data suggest progressively warmer temperatures and/or less winter precipitation through time (Cerling, 1984; Wang and others, 1993; Smith and others, 1993).

The youngest stage ranges from 1.4 to 0.7 Ma and is only represented by data from the Rincon Arroyo section. Both $\partial^{13}C$ and $\partial^{18}O$ show an overall increase with decreasing age, suggesting less effective moisture, higher temperature, and/or a greater proportion of summer precipitation through time.

Other important features of the data set are differences in absolute isotopic values *between* the stratigraphic sections (figs. 5 and 6). The magnitude of between-site variability in isotopic composition in the Camp Rice Formation is 1 to 1.5 permil and is comparable to or less than multiple sample variability observed within the stratigraphic sections of Cerling and Hay (1986), Wang and others (1993), and Smith and others (1993). This magnitude of variability may well be the norm in pedogenic carbonate, and because it is substantially less than the stratigraphic variation, it is not considered by us, nor was it considered by Cerling and Hay (1986), Wang and others (1993), and Smith and others (1993), to mask the paleoclimatic signature.

The between-site variation in isotopic values may be, in part, more apparent than real, because of inherent inaccuracy in chronologic correlation. Assigning absolute ages to a particular paleosol is based on the position of that paleosol with respect to chron and subchron boundaries in the stratigraphic section. The more complete the magnetostratigraphic record the more accurately the paleosols in that section can be dated. The Camp Rice stratigraphic sections in this study display significant variability in "completeness" of the polarity reversal record. The Hatch Siphon section has a nearly complete Gauss record but a condensed Matuyama section with no subchrons. Thus, the ages of the paleosols in the Gauss part of the Hatch Siphon section are well constrained, but the ages of the Matuyama paleosols are averaged over the entire duration of the Matuyama. The record at Rincon Arroyo is just the opposite to that of Hatch Siphon in that the Matuyama record is nearly complete, but the Gauss record is less so. The least well constrained of all the paleosols in terms of age is the Lucero Arroyo section, which has a Gauss interval with no subchrons and a condensed Matuyama interval with one subchron of unknown affinity. Given these differences in quality of the magnetostratigraphic record among the stratigraphic sections, correlation of paleosols between sections is clearly less accurate than it appears in figures 5 and 6 and table 1. This fact serves to diminish the apparent between-site differences in isotopic values.

REGIONAL COMPARISON OF PALEOCLIMATE DATA

A variety of different types of data has been applied to the interpretation of Pliocene and early Pleistocene paleoclimate in the western United States. Each data set, whether it is based on pollen, megascopic plant fossils, vertebrate fauna, or sedimentary lithofacies, provides a unique perspective on paleoclimate. When combined, the data sets present a fairly comprehensive model of terrestrial paleoclimate. This discussion is restricted to a comparison of the isotopic data from the Camp Rice Formation with paleoclimate data from apparently coeval strata in southeastern California, Arizona, and the southern Great Plains. Especially significant is comparison of Camp Rice data with isotopic data from paleosols of the St. David Formation, southeastern Arizona (Wang and others, 1993; Smith and others, 1993). A summary of Pliocene paleoclimate data for a much larger area of the western United States is provided by Thompson (1991).

The interpretation that south-central New Mexico during the period from 3.1 to 2.5 Ma experienced more effective moisture and was cooler and/or received more winter precipitation than in subsequent stages is in general agreement with paleoclimatic data from adjacent regions. Analyses of alluvial and lacustrine lithofacies at Searles Lake, California (Smith, 1984) and spring-related carbonate rocks in the Amargosa desert, California (Hay and others, 1986) suggests that the period from approx 3.4 to 2.4 Ma ago (early late Pliocene) was a time of greater effective moisture than today. Moreover, the presence of fossils of giant land tortoises (*Geochelone*) in roughly coeval rocks in the southern Great Plains, north-central Arizona, and south-central New Mexico just north of the study area argue for relatively mild winter temperatures (Hibbard, 1960; Auffenberg, 1974; Graham, 1986; Lucas and Oakes, 1986; Czaplewski, 1987). Fossil land tortoises have also been found in Gauss-age strata (3.4-2.48 Ma) in the Camp Rice Formation within the present study area (G. Mack, unpublished data). Carbon and oxygen isotopic values from pedogenic carbonate of the St. David Formation, Arizona, are, in general, lowest between about 3.2 and 2.5 Ma, which is consistent with relatively cool temperatures and/or significant winter precipitation (Wang and others, 1993; Smith and others, 1993). The data from the St. David Formation, however, display an excursion toward heavier isotopes between 3.0–2.8 to 2.6 Ma, followed by a 1 to 1.5 permil decrease by 2.4 Ma (Wang and others, 1993; Smith and others, 1993). This excursion is not well developed in data from the Camp Rice Formation.

Sedimentologic data from Searles Lake (Smith, 1984) and the Amargosa desert (Hay and others, 1986) indicate a rather abrupt increase in aridity around 2.5 to 2.4 Ma ago, extending in the case of the Searles Lake data to 2.0 Ma and followed by a period of relatively dry, but fluctuating paleoclimate until about 1.3 Ma. Oxygen isotopes of the Camp Rice Formation also show a dramatic increase at about 2.5 Ma, but no such dramatic increase is evident in the carbon data. The mean annual temperature remained cooler than today, however, based on pollen analyses at Rita Blanca, north Texas (Harbour, 1969) and at Safford and San Simon valleys, southeastern Arizona (Gray, 1961). The presence of *Geochelone* in north Texas (Thompson, 1991) and in south-central New Mexico just north of the present study area (G. Mack, unpublished data) suggests moderate, perhaps frost-free, winter temperatures. Carbon and oxygen isotopic data of the St. David Formation also increase over the interval from 2.4 to 1.4 Ma, suggesting progressively less winter precipitation and/or warmer temperatures (Wang and others, 1993; Smith and others, 1993). A similar increase in $\partial^{18}O$ exists in the Camp Rice Formation, but there is little significant change in $\partial^{13}C$.

There is an overall increase in both carbon and oxygen isotopes from 1.4 to 0.7 Ma in both the Camp Rice and St. David Formations, suggesting progressively less effective moisture, more summer precipitation, and/or higher temperatures (Wang and others, 1993; Smith and others, 1993). During the same time interval, Searles Lake experienced relatively dry, though fluctuating, paleoclimate, with a short interval of relatively high effective moisture from 1.28 to 1.0 Ma (Smith, 1984). The isotopic data of the Camp Rice and St. David Formations show a decrease in isotopic values around 1.0 Ma, but the data are too sparse to correlate it confidently with the wet period at Searles Lake. The paleoclimate in south-central New Mexico from 1.4 to 0.7 Ma was probably still milder than today, because of the presence in the Matuyama (2.48-0.7 Ma) part of the Camp Rice Formation of large mammals, such as glyptodonts, tapirs, ground sloths, horses, camels, and *Geochelone* (Vanderhill, 1986; G. Mack, unpublished data).

A combination of several factors probably contributed to the change in paleoclimate in the southwestern United States and southern Great Plains from late Pliocene through early Pleistocene time. It is beyond the scope of this paper to discuss all possible factors, but three in particular are noteworthy and are discussed in general here and in detail by Ruddiman and Raymo (1988) and Thompson (1991).

Temperatures cooler than today in the late Pliocene and early Pleistocene may reflect, in part, initiation of Northern Hemisphere glaciation. Ruddiman and Raymo (1988) suggest that small-scale glaciation may have begun as early as 3.15 Ma ago, whereas large-scale continental glaciation began abruptly at 2.4 Ma. This latter period corresponds closely in time to the increase in aridity at Searles Lake and in the Amargosa desert (Smith, 1984; Hay and others, 1986), as well as the dramatic increase in $\partial^{18}O$ of Camp Rice pedogenic carbonate.

Another potentially significant factor affecting paleoclimate of the southwestern United States and southern Great Plains was the orographic effect of the Sierra Nevada and Transverse Ranges of central and southern California. Huber (1981) suggests that the central Sierra Nevada has risen almost a kilometer since 3 Ma. Similarly, Winograd and others (1985) propose that much of the uplift of the Sierra Nevada and Transverse Ranges occurred in the last 1.2 Ma. As a consequence, Pacific moisture, most probably in the form of winter precipitation, had easier access to the southwestern United States and Great Plains in the late Pliocene and early Pleistocene than it does today. Progressive uplift of mountain ranges in California may have resulted in a systematic decrease in effective moisture and perhaps increase in seasonality of temperature and precipitation from late Pliocene through early Pleistocene.

Finally, General Circulation Model experiments by Kutzbach and others (1989) and Ruddiman and Kutzbach (1989) suggest that broad regional uplift of the western United States, independent of uplift of the Sierra Nevada and Transverse Ranges, may have had a significant influence on paleoclimate. Regional uplift may have caused, among other effects, a progressive trend toward colder winters as uplift proceeded.

CONCLUSIONS

Stable oxygen and carbon isotopes of pedogenic carbonate of the Camp Rice Formation and in strata inset against the Camp Rice Formation define three paleoclimatic stages. The first stage (3.1-2.5 Ma) is characterized by the lowest values of $\partial^{13}C$ and $\partial^{18}O$ and an increase in isotopic values with decreasing age, suggesting high effective moisture and abundant winter precipitation, which decreased through time, and/or a relatively low temperature that increased with time. Oxygen isotopes show an overall increase with decreasing age in the second stage (2.5-1.4 Ma), suggesting progressively higher temperatures and/or more summer precipitation, but carbon values show little variation with time. The final stage (1.4-0.7 Ma) displays an overall increase in both carbon and oxygen isotopes with decreasing age, indicative of less effective moisture, higher temperature, and/or greater summer precipitation through time. The paleoclimate changes observed in south-central New Mexico correlate closely with other paleoclimatic data from the southwestern United States and adjacent Great Plains and may have been caused by a combination of the onset of Northern Hemisphere continental glaciation, rise of the Sierra Nevada and Transverse Ranges, and broad regional uplift of the western United States.

ACKNOWLEDGMENTS

This study was funded in part by Petroleum Research Fund Grant 24378-B8 awarded to G. H. Mack and by grants from the New Mexico Bureau of Mines and Mineral Resources to G. H. Mack and S. L. Salyards. Support for D. R. Cole was provided by the Geosciences Program, Office of Basic Energy Sciences, U. S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Discussions with J. Horita and T. E. Cerling and comments by H. C. Monger and an anonymous reviewer greatly improved the manuscript.

REFERENCES

Auffenberg, W., 1974, Checklist of fossil land tortoises (Testudinidae): Florida State Museum Biological Sciences Bulletin, v. 18, p. 121–151.

Bachman, G. O., and Machette, M. N., 1977, Calcic soils and calcretes in the southwestern United States: U. S. Geological Survey Open-File Report 77–794, 163 p.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and late Pliocene to Holocene geomorphic history of the Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283–292.

Cerling, T. E., 1984, The stable isotopic composition of modern soil carbonate and its relationship to climate: Earth and Planetary Science Letters, v. 71, p. 229–240.

Cerling, T. E., and Hay, R. L., 1986, An isotopic study of paleosol carbonates from Olduvai Gorge: Quaternary Research, v. 25, p. 63–78.

Cerling, T. E., Hay, R. L., and O'Neil, J. R., 1977, Isotopic evidence for dramatic climatic changes in East Africa during the Pliestocene: Nature, v. 267, p. 137–138.

Cerling, T. E., and Quade, J., 1990, Global ecologic and climatic change during the Neogene: stable isotopic evidence from soils: Geochemistry of the Earth's Surface and of Mineral Formation, 2nd International Symposium, p. 164–165.

Czaplewski, N. J., 1987, Middle Blancan vertebrate assemblage from the Verde Formation, Arizona: University of Wyoming Contributions to Geology, v. 25, p. 133–155.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico-Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1965, The K horizon: a master soil horizon of carbonte accumulation: Soil Science, v. 99, p. 74–82.

———— 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347–360.

Graham, R. W., 1986, Plant-animal interactions and Pleistocene extinctions, *in* Elliot, D. K., editor, Dynamics of Extinction: Chichester, United Kingdom, John Wiley, p. 131–154.

Gray, J., 1961, Early Pleistocene paleoclimatic record from Sonoran Desert, Arizona: Science, v. 133, p. 38–39.

Gregory, R. T., Douthitt, C. B., Duddy, I. R., Rich, P. V., and Rich, T. H., 1989, Oxygen isotope composition of carbonate concretions from the Lower Cretaceous of Victoria, Australia: implications for the evolution of meteoric waters in the Australian continent in a paleopolar environment: Earth and Planetary Science Letters, v. 92, p. 27–42.

Harbour, J., 1969, Pollen profile of the Rita Blanca lake deposits: Geological Society of America Memoir 113, p. 83–95.

Hawley, J. W., 1981, Pleistocene and Pliocene history of the international boundary area, southern New Mexico: El Paso Geological Society, Geology of the Border-southern New Mexico-northern Chihuahua, p. 25–32.

Hay, R. L., Pexton, R. E., Teague, T. T., and Kyser, T. K., 1986, Spring-related carbonate rocks, Mg clays, and associated minerals in Pliocene deposits of the Amargosa Desert, Nevada and California: Geological Society of America Bulletin, v. 97, p. 1488–1503.

Hawley, J. W., and Kottlowski, F. E., 1969, Quaternary geology of the south-central New Mexico border region: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 89–104.

Hawley, J. W., Kottlowski, F. E., Seager, W. R., King, W. E., Strain, W. S., and LeMone, D. V., 1969, The Santa Fe Group in the south-central New Mexico border: New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 52–76.

Hibbard, C. W., 1960, An interpretation of Pliocene and Pleistocene climates in North America: Michigan Academy of Science, Arts and Letters Presidential Address 62, Annual Report, p. 5–30.

Huber, N. K., 1981, Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California-evidence from the upper San Joaquin River basin: U. S. Geological Survey Professional Paper 1197, 28 p.

Izett, G. A., Obradovich, J. D., Naeser, C. W., and Cebula, G. T., 1981, Potassium-Argon and fission-track zircon ages of Cerro Toledo Rhyolite tephra in the Jemez Mountains, New Mexico: U. S. Geological Survey Professional Paper 1199-D, p. 37–43.

Klappa, C. F., 1980, Rhizoliths in terrestrial carbonates: classification, recognition, genesis, and significance: Sedimentology, v. 27, p. 613–629.

Kortemeier, C. P., 1982, Occurrence of Bishop Ash near Grama, New Mexico: New Mexico Geology, v. 4, p. 22–24.

Kottlowski, F. E., 1953, Tertiary-Quaternary sediments of the Rio Grande valley in southern New Mexico: New Mexico Geological Society, Guidebook 4, p. 144–148.

Kutzbach, J. E., Guetter, P. J., Ruddiman, W. F., and Prell, W. L., 1989, Sensitivity of climate to late Cenozoic uplift in southern Asia and the American West: numerical experiments: Journal of Geophysical Research, v. 94, p. 18393–18407.

Lozinsky, R. P., and Hawley, J. W., 1986a, The Palomas Formation of south-central New Mexico-a formal definition: New Mexico Geology, v. 8, p. 73–78.

———— 1986b, Upper Cenozoic Palomas Formation of south-central New Mexico: New Mexico Geological Society, Guidebook 37, p. 239–247.

Lucas, S. G., and Oakes, W., 1986, Pliocene (Blancan) vertebrates from the Palomas Formation, south-central New Mexico: New Mexico Geological Society, Guidebook 37, p. 249–255.

Machette, M. N., 1985, Calcic soils of southwestern United States: Geological Society of America, Special Paper 203, p. 1–21.

Mack, G. H., Cole, D. R., Giordano, T. H., Schaal, W. C., and Barcelos, J. H., 1991, Paleoclimatic controls on stable oxygen and carbon isotopes in caliche of the Abo Formation (Permian), south-central New Mexico, U.S.A.: Journal of Sedimentary Petrology, v. 61, p. 458–472.

Mack, G. H., and James, W. C., 1992, Calcic paleosols of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift, USA: Sedimentary Geology, v. 77, p. 89–109.

Mack, G. H., Salyards, S. L., and James, W. C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49–77.

Mack, G. H., and Seager, W. R., 1990, Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Plio-Pleistocene) in the southern Rio Grande rift: Geological Society of America Bulletin, v. 102, p. 45–53.

Mankinen, E. A., and Dalrymple, G. B., 1979, Revised geomagnetic polarity time scale for the inteval 0–5 m.y. B.P.: Journal of Geophysical Research, v. 84, p. 615–626.

McCrea, J. M., 1950, The isotope chemistry of carbonates and a paleotemperature scale: Journal of Chemical Physics, v. 18, p. 849–857.

Naylor, H., Turner, P., Vaughan, D. J., and Fallick, A. E., 1989, The Cherty Rock, Elgin: a petrographic and isotopic study of a Permo-Triassic calcrete: Geological Journal, v. 24, p. 205–221.

Quade, J., Cerling, T. E., and Bowman, J. R., 1989, Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in the southern Great Basin, United States: Geological Society of America Bulletin, v. 101, p. 464–475.

Reeves, C. C., 1965, Pluvial Lake Palomas, northwestern Chihuahua, Mexico and Pleistocene geologic history of south-central New Mexico: New Mexico Geological Society, Guidebook 16, p. 199–203.

———— 1969, Pluvial Lake Palomas, northwestern Chihuahua, Mexico: New Mexico Geological Society, Guidebook 20, p. 143–154.

Repenning, C. A., and May, S. R., 1986, New evidence for the age of lower part of the Palomas Formation, Truth or Consequences, New Mexico: New Mexico Geological Society, Guidebook 37, p. 257–259.

Reynolds, R. L., and Larsen, E. E., 1972, Paleomagnetism of Pearlette-like air-fall ash in the midwestern and western United States-a means of correlating Pleistocene deposits: Geological Society of America, Abstracts with Programs, v. 4, p. 405.

Ruddiman, W. F., and Kutzbach, J. E., 1989, Forcing of late Cenozoic Northern Hemispheric climate by plateau uplift in southern Asia and the American West: Journal of Geophysical Research, v. 94, p. 18409–18427.

Ruddiman, W. F., and Raymo, M. E., 1988, Northern Hemisphere climate regimes during the past 3 Ma: possible tectonic connections: Royal Society of London Philosophical Transactions, B 318, p. 411–430.

Seager, W. R., and Hawley, J. W., 1973, Geology of Rincon quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 101, 42 p.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87–99.

Smith, G. A., Wang, Y., Cerling, T. E., and Geissman, J. W., 1993, Comparison of a paleosol-carbonate isotope record to other records of Pliocene-early Pleistocene climate in the western United States: Geology, v. 21, p. 691–694.

Smith, G. I., 1984, Paleohydrologic regimes in the southwestern Great Basin, 0-3.2 my ago, compared with other long records of "global" climate: Quaternary Research, v. 22, p. 1–17.

Spell, T. L., Harrison, T. M., and Wolff, J. A., 1990, ^{40}Ar/^{39}Ar dating of the Bandelier Tuff and San Diego Canyon ignimbrites, Jemez Mountains, New Mexico: temporal constraints on magmatic evolution: Journal of Volcanology and Geothermal Research, v. 43, p. 175–193.

Strain, W. S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: Texas Memorial Museum Bulletin 10, 55 p.

Suchecki, R. K., Hubert, J. F., and Birney De Wet, C. C., 1988, Isotopic imprint of climate and hydrogeochemistry on terrestrial strata of the Triassic-Jurassic Hartford and Fundy rift basins: Journal of Sedimentary Petrology, v. 58, p. 801–811.

Tedford, R. H., 1981, Mammalian biochronology of late Cenozoic basins of New Mexico: Geological Society of America Bulletin, v. 92, p. 1008–1022.

Thompson, R. S., 1991, Pliocene environments and climates in the western United States: Quaternary Science Reviews, v., 10, p. 115–132.

Vanderhill, J. B., ms, 1986, Lithostratigraphy, vertebrate paleontology, and magnetostratigraphy of Plio-Pleistocene sediments in the Mesilla basin, New Mexico: Ph.D. dissertation, University of Texas, Austin, Texas, 305 p.

Wang, Y, Cerling, T. E., Quade, J., Bowman, J. R., Smith, G. A., and Lindsay, E. H., 1993, Stable isotopes of paleosols and fossil teeth as paleoecology and paleoclimate indicators: An example from the St. David Formation, Arizona, *in* Climate Change in continental isotopic records: Geophysical Monograph 78, p. 241–248.

Winograd, I. J., Szabo, B. J., Coplen, T. B., Riggs, A. C., and Kolesar, P. T., 1985, Two-million-year record of deuterium depletion in Great Basin ground waters: Science, v. 227, p. 519–522.