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Stable isotopes and soil-geomorphology as indicators of Holocene climate change, northern Chihuahuan Desert

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Coeval $\delta^{13}C$ shifts recorded in buried soils at both piedmont slope and basin floor sites in the northern Chihuahuan Desert indicate a major shift from C_4 grasses to C_3 desert-scrub between 7 and 9 ka. The age assignments are based on stratigraphic correlations to charcoal dates and carbon-14 dates of carbonate. This shift is synchronous with a period of cooling in the North Atlantic that may have triggered a period of drought in the south-western United States. Coinciding with this vegetation change, geomorphic evidence in Rio Grande, piedmont, and basin floor eolian environments indicates a major period of erosion. Subsequent gradual enrichment of pedogenic carbonate $\delta^{13}C$ values in younger deposits suggests that C_4 grasses rebounded in the late Holocene (approximately 4 ka), which is consistent with other evidence of increased moisture regionally. A period of less severe aridity at approximately 2·2 ka is indicated by erosion and subsequent deposition along the alluvial fans and within the basin, and correlates with depleted pedogenic carbonate $\delta^{13}C$ values suggesting a decrease in C_4 grasses. Isotope and packrat midden records should be used together to infer past environmental conditions at different elevations.

Keywords: stable isotopes; geomorphology; paleoclimate; Chihuahuan Desert; Holocene

Introduction

Worldwide climatic changes marked the late Pleistocene to early Holocene transition. One of the most well known, and until recently, considered to be the last, abrupt climatic oscillation is the Younger Dryas, at approximately 12 ka (Mayewski *et al.*, 1993; Taylor *et al.*, 1997; Severinghaus *et al.*, 1998). However, a younger climatic shift has been documented in ice cores from Greenland and indicates a period of increased cooling (at approximately half the magnitude of the Younger Dryas) in the North Atlantic at 8·2 ka (Alley *et al.*, 1997). Modelling suggests that this cooling could trigger a period of drought in western North America (Benson *et al.*, 1997; Mikolajewicz *et al.*, 1997). Isotopic studies of sediment cores from Owens Lake in California support this theory (Benson *et al.*, 1997). Other studies show regional climatic changes worldwide, which supports the contention that this event had global implications (Alley *et al.*, 1997). In this

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paper, evidence is presented to show that a major climatic shift, which regionally appears to be of greater magnitude than the Younger Dryas, occurred in the early Holocene in the northern Chihuahuan Desert. Stable isotopic analyses of buried soils indicate a major change in vegetation (indicative of increased drought) occurred between 7–9 ka and the resulting geomorphic response was not controlled by landscape position, but can be seen in fluvial, alluvial, and eolian environments.

Setting

The Tularosa and Hueco basins comprise the northern-most extent of the Chihuahuan Desert (Fig. 1). Structurally, these north–south trending basins make up one of the eastern-most extensions of the Rio Grande Rift. The majority of the these basins are controlled by White Sands Missile Range, Holloman Air Force Base, and Fort Bliss Army Reservation. The basins are bounded by the Sacramento and Hueco mountains on the east, and the San Andres, Organ and Franklin mountains on the west (Fig. 1). A system of high-angle normal faults bound the eastern side of the San Andres, Organ, and Franklin mountains and show considerable Quaternary movement (Gile, 1987; Machette, 1987). An intricate system of north–south trending, en echelon intrabasinal faults are present along the basin floor in the southern Tularosa and northern Hueco basins (Seager, 1980). Basin floor elevation ranges between approximately 1196 and 1250 m, and adjacent mountain ranges can be up to 2725 m in elevation. In contrast to sediments along the adjacent Mesilla and Jornada basins, which are comprised mostly of fluvial Rio Grande deposits, late Quaternary sediments along the Tularosa and Hueco basin floors are dominated by eolian processes or, in some localized areas, by lacustrine playa deposits.

The climate is characterized by hot, arid conditions (average daily temperatures vary between 13 and 36°C), and highly variable annual precipitation ($\sim$ 20–24 cm year^{-1}). The majority of the annual precipitation is derived from intense, highly localized summer thunderstorms originating from the Gulf of Mexico. This is combined with some low-intensity winter precipitation resulting from frontal storms over the Pacific Ocean (Gile *et al*., 1981; Blair *et al*., 1990).

Much of the information about late Quaternary environments within the arid Southwest has been interpreted from pollen and packrat middens (Hall, 1985; Van Devender, 1990; Van Devender, 1995) and pluvial lakes (Waters, 1989). However, in arid environments pollen is vulnerable to degradation and packrat middens are preserved in only a limited range of environments, whereas calcic soils available for stable carbon and oxygen isotopic analysis are almost ubiquitous (Cerling, 1984; Amundson *et al*., 1989; Quade *et al*., 1989; Kelly *et al*., 1991). In this locality, the arid climate combined with the eolian processes along the Tularosa and Hueco basin floors precluded pollen preservation. Therefore, in this study the isotopic composition of pedogenic carbonate in buried soils was used as a proxy for late Pleistocene and Holocene climate change.

Isotopic values of pedogenic carbonate as a paleoclimatic indicator

Plant-respired CO_2 in the soil is depleted in ^{13}C because of the biochemical properties of the CO_2-fixing enzymes and the diffusion of CO_2 into the leaf during photosynthesis (O'Leary, 1988). There are two major plant photosynthetic pathways: C_4 and C_3, and each pathway fractionates carbon to a different extent. C_4 plants respire CO_2 that is enriched in ^{13}C by approximately 14‰ as compared to C_3 plants (Boutton, 1991). The $\delta^{13}C$ values of pedogenic calcium carbonate are a function of the soil CO_2, so this isotopic signature can be used to infer the type of plants living at the surface at the time of carbonate formation. Thus, in pure C_3 plant communities, the pedogenic

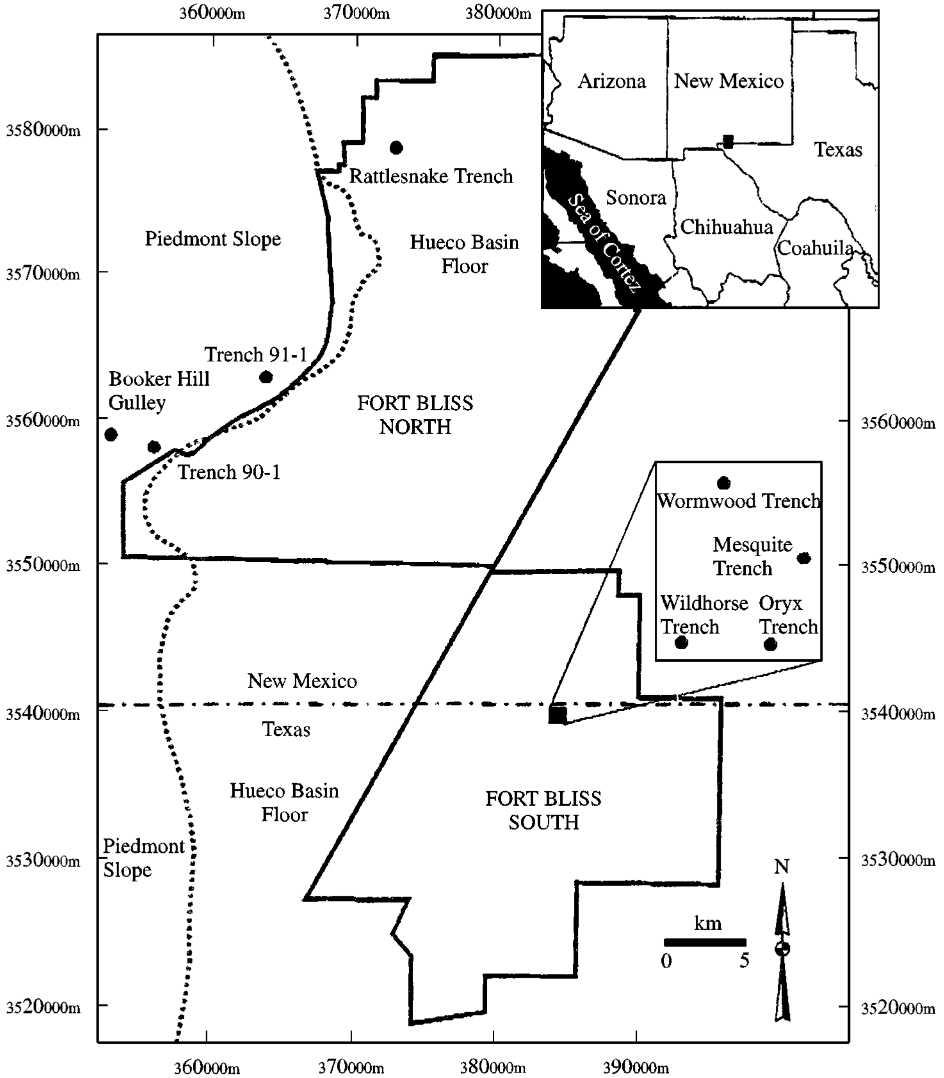

Figure 1. Study area located in the Hueco Basin, Fort Bliss Military Reservation, northern Chihuahuan Desert. Stable isotopic analyses of pedogenic carbonate were performed on five buried soil profiles located in eolian sediments in or adjacent to intrabasinal fault troughs on the basin floor (Rattlesnake, Wildhorse, Oryx, Mesquite and Wormwood Trenches), and three buried soil profiles located in alluvial sediments on the fan-piedmont (Booker Hill Gully, Trench 90-1, Trench 91-1). Map co-ordinates are in the UTM (Universal Tranverse Mercator) co-ordinate system.

carbonate $\delta^{13}C$ values should approximate $-12‰$, and pure C_4 communities should be $+1$ or $+2‰$ at 25°C (Quade *et al.*, 1989; Boutton, 1991).

In the Chihuahuan Desert, warm-season grasses, such as Black grama (*Boutelous eriopoda*), Mesa dropseed (*Sporobolus flexuosus*), and Red threeawn (*Aristida purpurea*), utilize the C_4 photosynthetic pathway. This pathway is also used by one common shrub, the Fourwing saltbush (*Artriplex canescens*) (Syvertsen *et al.*, 1976). However, most desert shrubs, including Honey Mesquite (*Prosopis glandulosa*), Tarbush (*Flourensia cernus*), and Creosotebush (*Larrea tridentata*), use the C_3 pathway. The C_3 pathway is also utilized by pinyon, juniper and other conifers in more humid climates or at higher elevations.

Presently in the Chihuahuan Desert, grasslands are found on stable landscape surfaces with little or no erosion. In contrast, areas dominated by desert shrubs have an increased surface area of bare ground, which results in increased eolian erosion and landscape instability. In this study, Holocene buried soils that contain a C_3 isotopic signature are interpreted to represent desert scrub based on (1) their correlation to periods of increased erosion; (2) increases in Chenopodiaceae and Amaranthaceae pollen in the same stratigraphic units along adjacent alluvial fans (Freeman, 1972; Monger *et al*., 1998), which is interpreted as indicators of desert scrub vegetation (Brown, 1982; Gish, 1993); and (3) the absence today of pinyon or juniper in the lower elevations of the Chihuahuan Desert. Thus, unlike many δ^{13}C study locations (Quade *et al*., 1989), within this area, a C_3 isotopic signature is interpreted as an indication of aridity.

Late Quaternary stratigraphy

Holocene sediments in the study area and surrounding basins include the Organ allostratigraphic unit on the piedmont slopes and the Fillmore unit bordering the Rio Grande (Tables 1, 2) (Hawley, 1965; Ruhe, 1967; Gile *et al*., 1981). These units are mapped based on their weak soil development characterized by stage I carbonate filaments and/or pebble coatings (Gile *et al*., 1966), and their lowest geomorphic position, which is graded very close to the modern arroyo system. The Organ unit disconformably overlies a series of Pleistocene paleosols as alluvial fans, valley fill, and colluvial deposits. The youngest radiocarbon date of a charcoal deposit in the Leasburg allostratigraphic unit, which the Fillmore deposit either is inset against or overlaps, is 9360 B.P. (Table 2). Distinct breaks in sedimentation and radiocarbon ages of charcoal deposits indicate at least two major episodes of alluviation during the Holocene. Fillmore

Table 1. *Late Quaternary eolian and playa stratigraphy of the northern Hueco basin. Asterisk (*) indicates uncommon occurrence (after Buck* et al., *1998*)

Eolian/basin floor		
Deposit	Carbonate morphology	Age
Historic Blowsand	no carbonate	100–150 year (Historical)
Organ III	no carbonate	100?–1100 years B.P.
Organ II*	faint stage I	1100–2100 years B.P.
Organ I	stage I	2200–7000 years B.P.
Isaacks' Ranch	stage II	8–15 ka (early Holocene–late Pleistocene)
Jornada I and II*	stage II–III	25–400 ka (middle-late Pleistocene)
La Mesa	stage III–IV	$>$400 ka (early-middle Pleistocene)
Playa/basin floor		
Playa deposit		Age
Lake Tank*		Present to late Pleistocene
Petts Tank*		Late Pleistocene (25–75 ka)

Table 2. *Late Quaternary alluvial and fluvial stratigraphy of south-central New Mexico (after Gile* et al., *1981*)

Deposit	Carbonate morphology	Age
Alluvial/piedmont slope		
Arroyo channels/Historic Blowsand	no carbonate	100–150 year (Historical)
Organ III	no carbonate	100?–1100 years B.P.
Organ II	faint stage I	1100–2100 years B.P.
Organ I	stage I	2200–7000 years B.P.
Isaacks' Ranch	stage II	8–15 ka (early Holocene to late Pleistocene)
Jornada I and II	stage II–III	25–400 ka (middle-late Pleistocene)
Doña Ana	stage III–IV	>400 ka (early-middle Pleistocene)
Fluvial/valley border		
Arroyo channels/Historic Blowsand	no carbonate	100–150 year (Historical)
Fillmore	stage I	100?–7000 years B.P.
Leasburg	stage II	8–15 ka (early Holocene to late Pleistocene)
Picacho, Tortugas, Jornada I	stage II–III	25–400 ka (middle-late Pleistocene)
La Mesa	stage III–IV	>400 ka (early-middle Pleistocene)

and Organ alluvium contains charcoal dated to 7340 B.P. and 6400 B.P. respectively, indicating sedimentation was initiated prior to those times and ceased about 4000 B.P. (Gile *et al.*, 1981). A second episode of alluviation was initiated about 2200 B.P. (Table 2) (Gile *et al.*, 1981).

Recent geomorphic mapping revealed that an eolian Organ unit can be traced across much of the basin floor on the Fort Bliss Military Reservation (Buck, 1996; Buck *et al.*, 1998; Table 1). This eolian Organ unit is also characterized by its weak profile development, stage I carbonate filaments, and in many areas, its disconformable position overlying well-developed paleosols containing argillic and calcic horizons (Table 1, Fig. 2). Underlying late Pleistocene eolian deposits can also be correlated to alluvial deposits along adjacent fans, and contain similar soil morphologies (Tables 1, 2). The eolian Organ unit is overlain by coppice dunes and sand sheets of Historic age (<150 years; Gile, 1975; Tables 1, 2).

Some of the best preserved Organ soils within the basin are found on the hanging wall blocks of intrabasinal Quaternary normal faults, where subsidence adjacent to the faults accommodated deposition of eolian sediments (Fig. 2) (Buck, 1996; Buck *et al.*, 1998). The high rates of eolian sedimentation adjacent to these faults resulted in an aggradational environment without many of the disconformities found elsewhere in the region. Additionally, the high rate of sedimentation continuously buried young developing soils.

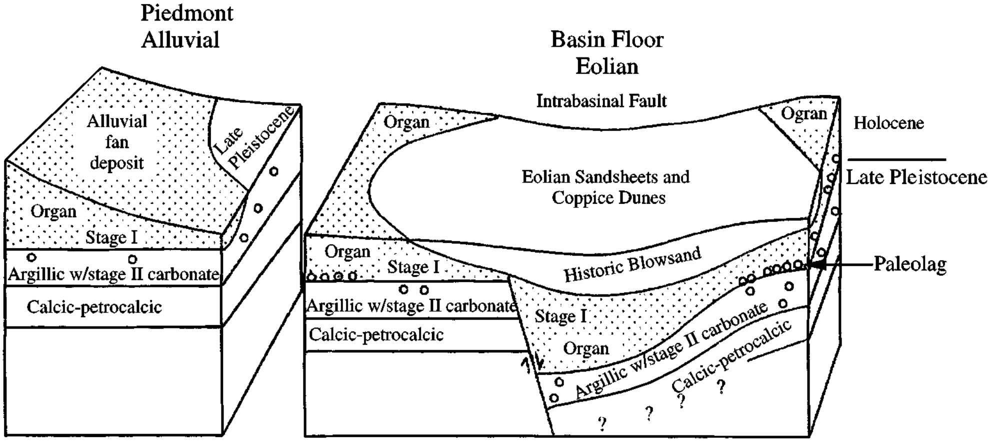

Figure 2. Idealized block diagram showing region-wide erosion and subsequent deposition of the Organ unit after the major vegetation transition between 7–9 ka. However, intrabasinal normal faults within the Hueco Basin experienced continuous deposition and contain a relatively complete record.

The result is a thick interval of stage I filaments of pedogenic carbonate. Continued aggradation also curtailed contamination from younger, downward-percolating soil waters and soil carbonate formation. We hypothesized that these areas have the potential to contain a relatively continuous isotopic record of past climate. The research described here measured the δ^{13}C and δ^{18}O values of the pedogenic calcium carbonate preserved within these stratigraphically expanded sections adjacent to the intrabasinal faults and compared them to previously published coeval isotopic shifts found in soils developed on adjacent alluvial fans (Fig. 1) (Cole & Monger, 1994).

Methods

Approximately 140 profiles were excavated and described within the northern Hueco and southern Tularosa basins to determine (1) the stratigraphy and (2) to locate the areas with the most continuous Holocene sedimentary record. The eolian basin floor trenches described in Monger *et al.*(1998) did not contain the expanded Holocene stratigraphy needed for detailed paleoclimatic interpretation. Therefore, it was hypothesized that areas near the north–south trending intrabasinal normal faults contain the most complete stratigraphy, and 81 trenches were located along or near eight of these faults. Five trenches (Mesquite, Rattlesnake, Oryx, Wildhorse, and Wormwood) across two faults contained the most complete stratigraphic record and were excavated approximately 3–4 m deep. Additionally, these five trenches were chosen to reflect the basin as a whole: Mesquite trench was located along one of the topographically highest portions of an upthrown block; Oryx and Wildhorse trenches are on the topographically lowest positions of a downthrown block; and Rattlesnake and Wormwood trenches occupy topographically intermediate areas.

Samples of stage I filaments and in a few cases, incipient stage II nodules were taken from these five freshly excavated profiles at 10 cm intervals for isotopic analyses. On three of the five trenches (Oryx, Wildhorse, and Wormwood), samples were taken at two lateral transects, 10, 20, and 30 cm apart, to determine the lateral variability within each profile. The error bars accompanying these profiles show the mean and standard deviation from the two transects at each locality (Fig. 3(e, f, h)). The samples were

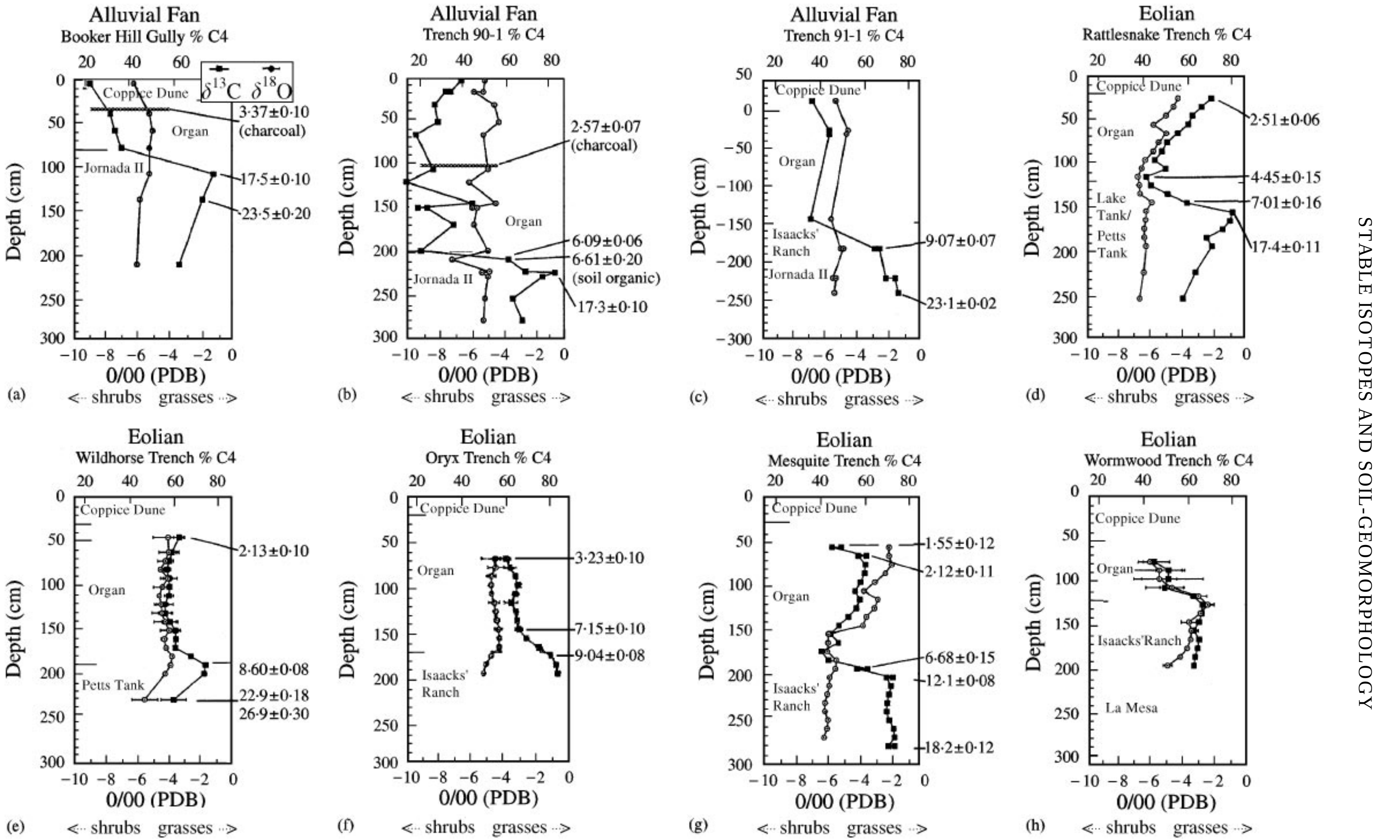

Figure 3. Stable isotopic composition of pedogenic carbonate in eight buried soil profiles. Isotopic compositions are expressed as δ-values in parts per mil relative to the PDB standard, black squares are $\delta^{13}C$ values and open circles are $\delta^{18}O$ values. Unless otherwise stated, ^{14}C dates are of pedogenic carbonate (see text for explanation) and are in units of ka (= 1000 years). % C_4 biomass is based on the model by Cerling (1984). All eight profiles record a major shift in $\delta^{13}C$ values coeval with the erosional event that preceded deposition of the Organ unit: <······ , shrubs; ······> , grasses.

sieved with a 177 μm sieve to concentrate the pedogenic carbonate, which generally ranges from 1 to 5 μm in diameter (Monger *et al.*, 1991), and to eliminate any older nodular carbonate rubble sometimes associated with the fault scarps. Oxygen and carbon isotopic measurements were determined at New Mexico Tech Stable Isotopic Laboratory. Conventional inorganic radiocarbon dating and stable isotope analysis of specific samples were performed by Beta Analytic Inc. Texture on specific profiles was determined by feel according to the flow chart by Thein (1979). Soil colour was determined using the Munsell soil colour chart. Carbonate morphogenetic sequences were based on the classification of Gile *et al.* (1966). Stratigraphic units were compared and correlated with those used on the adjacent alluvial fans of the Organ Mountains (Gile *et al.*, 1981; Monger, 1995).

Carbon-14 dates of carbonate

Although the Organ chronostratigraphic unit is based on numerous charcoal radiocarbon dates (Gile, 1975; Gile *et al.*, 1981), radiocarbon dates of pedogenic carbonate were measured in this study for comparison purposes. The results indicate that pedogenic ^{14}C dates are consistent with the ages of Organ sediments as determined by charcoal, geomorphic position, soil morphology, and are consistent with stratigraphic position, reflecting the aggrading environment in which they formed (Figs 3, 4, 5). However, these dates can only be used as approximations according to models by Wang *et al.* (1996), and Amundson *et al.* (1994).

The processes which control the ^{14}C signature of pedogenic carbonate are the same as those that control the ^{13}C signature: the carbon is derived primarily from the respiration of CO_2 by plants, and the decomposition of organic matter. Previous studies indicate that pedogenic carbonate that precipitates at 30 cm depth or greater and in areas with low soil organic matter, should be useful for radiogenic dating (Cerling & Quade, 1993; Wang *et al.*, 1994). However, like ^{13}C, ^{14}C dates of pedogenic carbonate are a cumulative average and, therefore, will be greatly controlled by morphology. Radiocarbon ages of morphologies associated with a low stage of carbonate accumulation, such as stage I filaments, represent a shorter time span than radiocarbon ages on carbonate of stage II or higher, which integrate the larger time spans necessary to form those morphologies (Gile *et al.*, 1966; Machette, 1985). Therefore, stage I carbonates that precipitated in an aggrading environment and were subsequently removed from the zone of pedogenesis provide more temporal resolution than homogenized samples from carbonate that coalesced into nodules or petrocalcic horizons in soils on non-aggrading surfaces.

Although pedogenic carbonates are time transgressive, their radiocarbon ages appear to be useful in this particular study for several reasons: (1) these arid eolian soils typically have low organic matter contents (generally much less than 1%) and contamination from decomposition of older organic matter is probably negligible; (2) samples were taken from stage I filaments, and a few incipient stage II nodules, for which micromorphology indicates *in situ* precipitation, thus preventing the possibility of calcareous dust contamination (Monger *et al.*, 1998); (3) the carbonate sampled is beneath the modern wetting front, therefore protected from younger contamination (Buck, 1996); (4) parent material is non-calcareous, so detrital carbonate is negligible; (5) ^{14}C dates of associated charcoal from both the basin floor and adjacent alluvial fans correlate to both the ^{14}C dates of pedogenic carbonates and the geomorphic surface in which they occur; (6) $\delta^{13}C$ values of soil organic matter in correlating geomorphic units along adjacent alluvial fans are consistent with that from pedogenic carbonate, and pollen analyses (Monger *et al.*, 1998), indicating that the $\delta^{13}C$ values of the pedogenic carbonate are intact, and therefore, $\delta^{14}C$ values should be as well; (7) finally, all ^{14}C dates of pedogenic carbonate within the basin floor and adjacent alluvial fans are consistent with stratigraphic position (Figs 3, 4, 5).

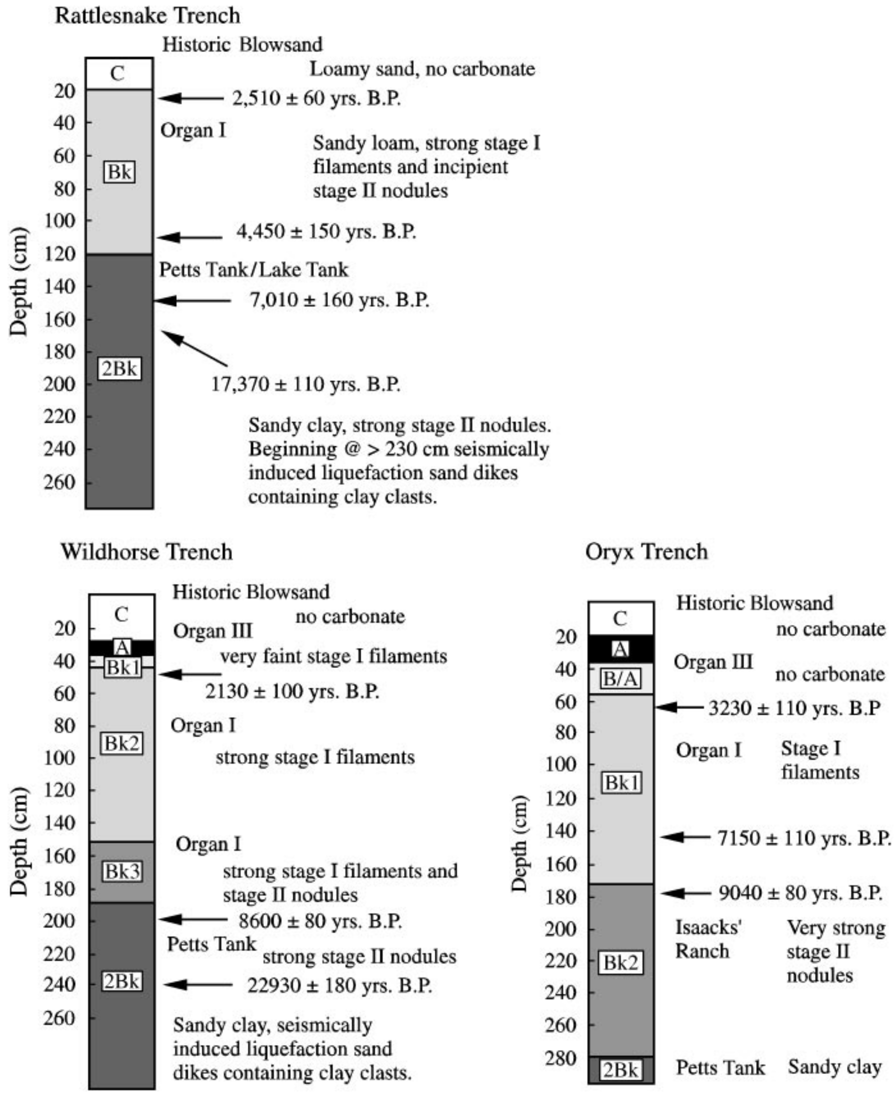

Figure 4. Soil-stratigraphy of eolian profiles in Rattlesnake, Wildhorse, and Oryx trenches. ^{14}C dates are from pedogenic carbonate.

Results

$\delta^{13}C$ values

Soil stratigraphy and abbreviated profile descriptions for the five eolian profiles that were sampled for isotopic analyses are shown in Fig. 4 and 5. Radiocarbon dates were obtained from stage I filaments of pedogenic carbonate. Figure 3 compares the isotopic shifts in soils developed on basin-margin alluvial fans (Fig. 3(a, b, c)) with those in the eolian strata of the basin interior (Fig. 3(d, e, f, g, h)).

All five eolian and three alluvial profiles record similar coeval basin-wide paleoenvironmental changes. Four major trends are evident in these profiles: (1) in the eolian profiles, carbonate found in playa deposits, which correlate regionally to deposits older

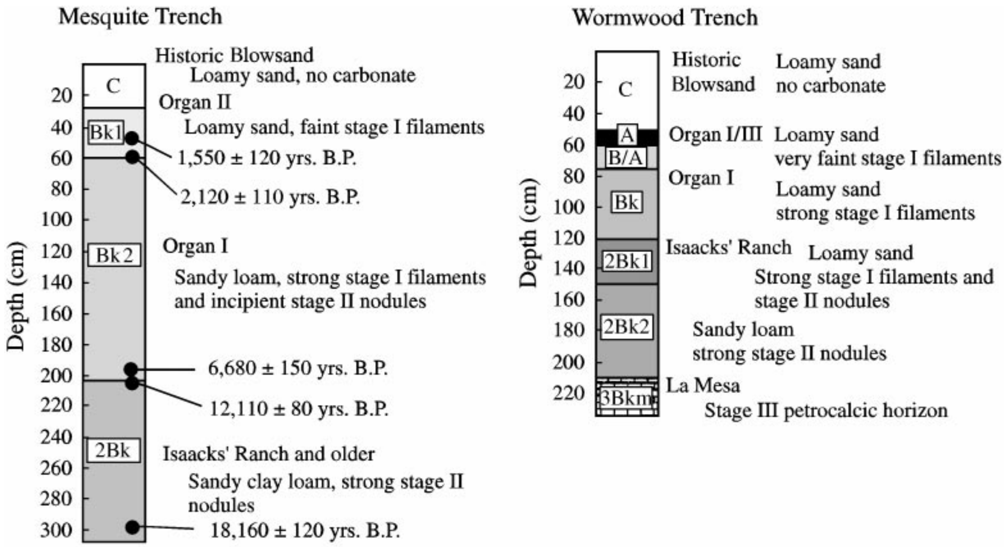

Figure 5. Soil-stratigraphy of eolian profiles in Mesquite and Wormwood trenches. ^{14}C dates are from pedogenic carbonate.

than 18 ka (radiocarbon date from carbonate), have depleted carbonate $\delta^{13}C$ values (Fig. 3(d)). Depleted carbonate $\delta^{13}C$ values are also found in two of the alluvial fan deposits of similar age (Fig. 3(a, b)); (2) enriched carbonate $\delta^{13}C$ values peak in the late Pleistocene paleosols above these deposits (Fig. 3(d, e, f, g, h)); (3) an abrupt and large depletion in carbonate $\delta^{13}C$ values between 7 and 9 ka (^{14}C of both organic carbon and carbonate *in situ* and from stratigraphic correlation) immediately precedes or coincides with the deposition of the Organ sediments in all five eolian profiles as well as all three alluvial profiles (Fig. 3); (4) two of the five eolian profiles record a rebound to more enriched $\delta^{13}C$ values after approximately 4 ka (radiocarbon date from carbonate; Fig. 3(d, g)).

In two of the eolian profiles, stage I and II pedogenic carbonate with depleted $\delta^{13}C$ values is found in late Pleistocene (greater than 18 ka, radiocarbon date from carbonate), fine-grained playa sediments (Fig. 3(d, e)). These two previously unknown playas were buried by sand and correlate regionally with late Pleistocene strata (Fig. 4, Table 1) based on geomorphic position and soil profile development (Gile *et al.*, 1981). Depletion of carbonate $\delta^{13}C$ values in playa deposits suggests a localized increase in C_3 plants such as the Common cattail (*Typha latifolia*) or other C_3 plants associated with wet or marshy areas. However, a similar depletion in carbonate $\delta^{13}C$ values is also present in two of the three alluvial profiles (Fig. 3(a, b)). Because these profiles do not contain fine-grained playa sediments, yet have a similar shift in carbonate $\delta^{13}C$ values, an alternative interpretation of a late Pleistocene (greater than 18 ka, radiocarbon date from carbonate) savanna comprised of a mixed community of C_3 pinyon-juniper-oak and C_4 grasses is plausible.

All latest Pleistocene paleosols (younger than 18 ka, radiocarbon date from carbonate), both alluvial and eolian, contain enriched carbonate $\delta^{13}C$ values indicative of a landscape dominated by C_4 grasses. C_4 grasses comprised up to 80% of the vegetation according to the $\delta^{13}C$ model by Cerling (1984). The greatest enrichment occurs in both the alluvial and eolian profiles between about 8 and 18 ka (radiocarbon date from carbonate) (Fig. 3(a, b, c, d)).

The largest isotopic shift (up to $> 8\%$) found in this study occured at the onset of the deposition of the Organ sediments. The enriched $\delta^{13}C$ values of the latest Pleistocene paleosols became significantly depleted—C_4 grasses drop to nearly 40% of vegetation in the eolian profiles and even lower in the alluvial profiles—either just prior to, or coinciding with the deposition of the Organ sediments (Fig. 3).

Lastly, two of the five eolian profiles show a rebound in carbonate $\delta^{13}C$ values in the upper portion of the Organ deposit (Fig. 3(d, g)). This enrichment indicates the return of a greater percentage of C_4 grasses—nearly returning to the late Pleistocene values of 80% grasses in Rattlesnake Trench (Fig. 3(d)). In the Mesquite trench, this enrichment is followed by another depletion in carbonate $\delta^{13}C$ values, which is present in the uppermost portion of the Organ deposit (Fig. 3(g)).

Three of the five eolian profiles were sampled and analysed along lateral transects to determine any lateral variation in carbonate $\delta^{13}C$ values. No significant lateral variations were observed in Oryx and Wildhorse trenches (Fig. 3(e, f)). Larger variations were observed in the Organ deposit of Wormwood trench (Fig. 3(h)), which contained physical evidence of extensive burrowing and further strengthens the argument to avoid sampling such areas (Fig. 5).

$\delta^{18}O$ values

All of the processes involved with the fractionation of oxygen in soils are not well understood (Amundson *et al.*, 1994; Wang *et al.*, 1996). There is, however, a correlation between the $\delta^{18}O$ values of pedogenic carbonates and meteoric water (Cerling & Quade, 1993). Therefore, it may be possible to infer mean annual temperatures from pedogenic carbonate $\delta^{18}O$ values (Hays & Grossman, 1991), although recent research suggests that $\delta^{18}O$ values of pedogenic carbonate may be most useful in identifying past storm sources (Amundson *et al.*, 1996).

Soil carbonate $\delta^{18}O$ values found in the late Pleistocene paleosols and the lower portions of the Organ deposit are generally similar to late Holocene values. These $\delta^{18}O$ values point to mean annual temperatures only slightly cooler than today (Liu *et al.*, 1996). These depleted $\delta^{18}O$ values remain relatively unchanged during the massive shift in $\delta^{13}C$ values correlating to the onset of the deposition of the Organ sediments. However, $\delta^{18}O$ values become enriched in the upper portion of the Organ deposit in two of the eolian profiles (Fig. 3(d, g)).

Discussion

The eight profiles in this study record basin-wide vegetational changes, which correspond regionally to geomorphic changes in Rio Grande, alluvial fan and eolian environments. Enriched carbonate $\delta^{13}C$ values in the late Pleistocene paleosols are interpreted to represent an increase in the abundance of C_4 grasses instead of a decrease in plant density and associated low respiration rates (Wang *et al.*, 1996). This scenario is mutually supported by an increase in Gramineae pollen in the alluvial fan deposits (Monger *et al.*, 1998), and soil-geomorphic evidence of landscape stability and soil formation.

The largest paleoenvironmental change documented in this study occurred at the beginning of the middle Holocene, between 7 and 9 ka (age constraints based on region-wide ^{14}C analyses on both organic and inorganic materials, and stratigraphic correlations) (Gile *et al.*, 1981; Monger, 1995; Buck, 1996; Monger *et al.*, 1998). Within this study, all eight profiles contain abrupt shifts to depleted carbonate $\delta^{13}C$ values and indicate that the C_4 grassland was abruptly replaced by a C_3 vegetational community composed of desert shrubs. This interpretation is mutually supported by a decrease in Gramineae pollen and a sharp increase in Chenopodiaceae and Amaranthaceae pollen in the alluvial fan stratigraphy (Freeman, 1972; Monger *et al.*, 1998). Within the eolian environments of the Hueco Basin, this increase in C_3 desert shrub may also have caused an increase in the percentage of bare ground, which resulted in increased rates of eolian erosion, and was followed by the deposition of the Organ sediments on both the alluvial fans and the basin floor (Tables 1, 2). In some places, stage II carbonate nodules from the underlying Pleistocene paleosols were exhumed during this deflation event and accumulated as a lag at the surface (Blair *et al.*, 1990). This lag was later buried in some places by the Organ sediments (Fig. 2). Additionally, along the Rio Grande, this time period is marked by aggredation and deposition of the Fillmore alluvium (Table 2).

The causes behind this abrupt shift in vegetation in the northern Chihuahuan Desert may be of a global extent. Ice cores from Greenland document a cold, dry, windy event in the North Atlantic at 7500 ^{14}C. B.P. (Alley *et al.*, 1997). Both climate simulations and field evidence suggest that cooling of the North Atlantic correlates to periods of aridity in south-western North America (Benson *et al.*, 1997). Paleolake levels throughout the south-west are low during this time (Smith & Street-Perrott, 1983; Waters, 1989; Hawley, 1993; Benson *et al.*, 1997). δ^{18}O values of pedogenic carbonate in this study and at Owens Lake (Benson *et al.*, 1997) remain relatively constant, suggesting that this arid interval was not coeval with an increase in mean annual temperatures. However, Liu *et al.* (1996) suggest that temperature controlled changes in the carbonate-water fractionation factor could produce these consistent values. Therefore, a possible increase in mean annual temperatures is not precluded; such a shift might have resulted in increased stress upon the late Pleistocene grassland. Additionally, the replacement of C_4 grasses by C_3 desert-scrub may have been enhanced by an increase in atmospheric CO_2 levels at the end of the Pleistocene, which favours plants with the C_3 photosynthetic pathway (Cole & Monger, 1994; Monger & Cole, 1994; Ehleringer *et al.*, 1997).

A return to more enriched carbonate δ^{13}C values representing an increase in C_4 grasses in the late Holocene occurs in two of the eolian profiles (Fig. 3(d, g)). Stratigraphic and pollen data (Freeman, 1972; Gile, 1975; Buck, 1996) suggest that a period of landscape stability occurred near 4 ka (charcoal and carbonate dates). This stabilization and increase in C_4 grasses may have been aided by increased precipitation throughout the south-west indicated by: high magnitude floods in southern Utah and Arizona (which have been interpreted to coincide with periods of cool, wet climate); glacial advances; pollen analyses suggesting moist conditions in southern Arizona and California; high ground water levels in New Mexico, Colorado, and Nevada (see Ely, 1997); and paleolake levels in south-eastern Arizona (Smith & Street-Perrott, 1983; Waters, 1989; Hawley, 1993). Determining the seasonality of this increased precipitation is beyond the scope of this paper. However, possible evidence for an increase in summer precipitation may be found in enriched carbonate δ^{18}O values in the same two eolian profiles (Fig. 3(d, g)). These suggest an increase in mean annual temperatures, a change in storm source, and/or evaporation-driven enrichment possibly resulting from the development of summer precipitation. Presently, more than half of the mean annual precipitation falls during the summer months (Gile, 1993). During the late Pleistocene, the polar airstream is believed to have shifted southward, bringing much of the mean annual precipitation during the winter months (Van Devender, 1990). The input of polar air and winter precipitation is believed to have decreased as the continental glaciers retreated. Because increased summer precipitation favours C_4 grasses, enrichment in carbonate δ^{18}O values parallels enrichment in δ^{13}C values, and these isotopic shifts coincide with geomorphic evidence for landscape stabilization, the data may reflect the onset of the present-day summer monsoonal climate. However, a confident interpretation of monsoonal development based on the carbonate δ^{18}O data within this study is not yet possible.

On the alluvial fans adjacent to the Hueco Basin, a period of desertification at approximately 2·2 ka (charcoal radiocarbon dates) has been interpreted as the driving mechanism for the deposition of the Organ II unit along the alluvial fans (Gile, 1975; Gile *et al.*, 1981). In the Hueco Basin, this period of aridity is indicated by a shift toward lighter carbonate $\delta^{13}C$ values in Mesquite Trench (Fig. 3(g)). However, Organ II deposits in the basin are not easily distinguishable from Organ I sediments, suggesting that the period of aridity (Fairbanks drought; Gile, 1975) believed to have caused the deposition of the Organ II sediments along the alluvial fans was not severe enough to produce a distinct basin-wide eolian deposit on the basin floor. Interestingly, this drought (possibly recorded by the uppermost isotopic shift, Fig. 3(g)), corresponds to the Jornada Mogollon (Formative) period of cultural development, in which agriculture and ceramic use intensified in this region.

Differences between packrat midden studies and isotopic records show that vegetation patterns in the late Pleistocene and Holocene were topographically controlled, as they are today, and that the pedogenic isotope record in the lower elevations of piedmont slopes and basin floors should be used in conjunction with the packrat record to reconstruct vegetation dynamics (Table 3). Packrat midden research in the Hueco, Sacramento, and San Andres mountains surrounding the Hueco basin suggests changes in plant communities are uni-directional with increasing aridity from the late Pleistocene through to the Holocene (Table 3) (Van Devender, 1990; Van Devender, 1995). Although both records are in agreement about the timing of the major shifts in vegetation, the nature of the shifts differ. The packrat midden record suggesting the existence of a late Pleistocene C_3 woodland differs from the C_4 isotopic signature found in both alluvial and eolian environments in this study as well as in a similar basin in southern Arizona (Liu *et al.*, 1996). Similarly, packrat midden data indicate a shift to a C_4 grassland at approximately 7–9 ka, whereas depleted carbonate $\delta^{13}C$ values indicate C_3 desert-scrub. Although in both of those shifts the general trend in both midden and isotopic records is towards increasing aridity, the shift at approximately 4 ka is not. Packrat midden studies suggest a period of increased aridity at approximately 4 ka, indicated by a change from grassland to desert-scrub. In contrast, isotopic records from soil carbonates suggest a period of increased moisture, indicated by a change from desert-scrub to increased C_4 grasses. Further research is needed to explain this anomaly. However, overall, the differences in the packrat midden and isotopic records probably reflect differing microclimates associated with elevational gradients. For example, packrat middens are preserved in rocky cliffs, where overhangs and small caves form natural areas of protection. These areas will have different soil-climates than areas within the basin and along alluvial fans and will bias the packrat midden record towards those environments (Betancourt *et al.*, 1990; Liu *et al.*, 1996). Used together, these two types of data sets may provide significant insights for late Pleistocene

Table 3. *Comparison of packrat midden studies vs. isotopic records in the northern Chihuahuan Desert*

Timing of major vegetational shifts	Packrat middens* (rocky cliffs, higher elevations)	Isotope records (basin floor, alluvial fan environments)
Approx. 2·2 ka	desert-scrub (increase at 2·5 ka)	decrease grasses
Middle-late Holocene (approx. 4 ka)	desert-scrub	increased grasses
Early-middle Holocene(approx. 7–9 ka)	desert grassland	desert-scrub
Latest Pleistocene/early Holocene (approx. 11 ka)	oak, juniper woodland	desert grassland
Latest Pleistocene (approx. >15 ka)	pinyon, juniper, oak woodland	desert grassland

*Van Devender, 1990; Van Devender, 1995.

and Holocene environmental reconstructions. It is plausible that the northern Chihuahuan Desert during the late Pleistocene was characterized by desert grasslands along alluvial fans and within the eolian-dominated basins, but dominated by pinyon-juniper-oak woodlands with increasing elevation and along rocky canyons and hillslopes. The abrupt arid event between 7–9 ka resulted in a change to desert-scrub-dominated alluvial fans and basin floors with desert grasslands at higher elevations. Significantly, both packrat midden and soil carbonate isotopic records show major vegetation changes at approximately 7–9 ka, 4 ka, and 2·2 ka.

Conclusions

Shifts in $\delta^{13}C$ values of pedogenic carbonate in buried soils at both piedmont slope and basin floor sites in the northern Chihuahuan Desert indicate a major transition from C_4 grasses to C_3 desert-scrub between 9 and 7 ka (Fig. 6). The geomorphic response to

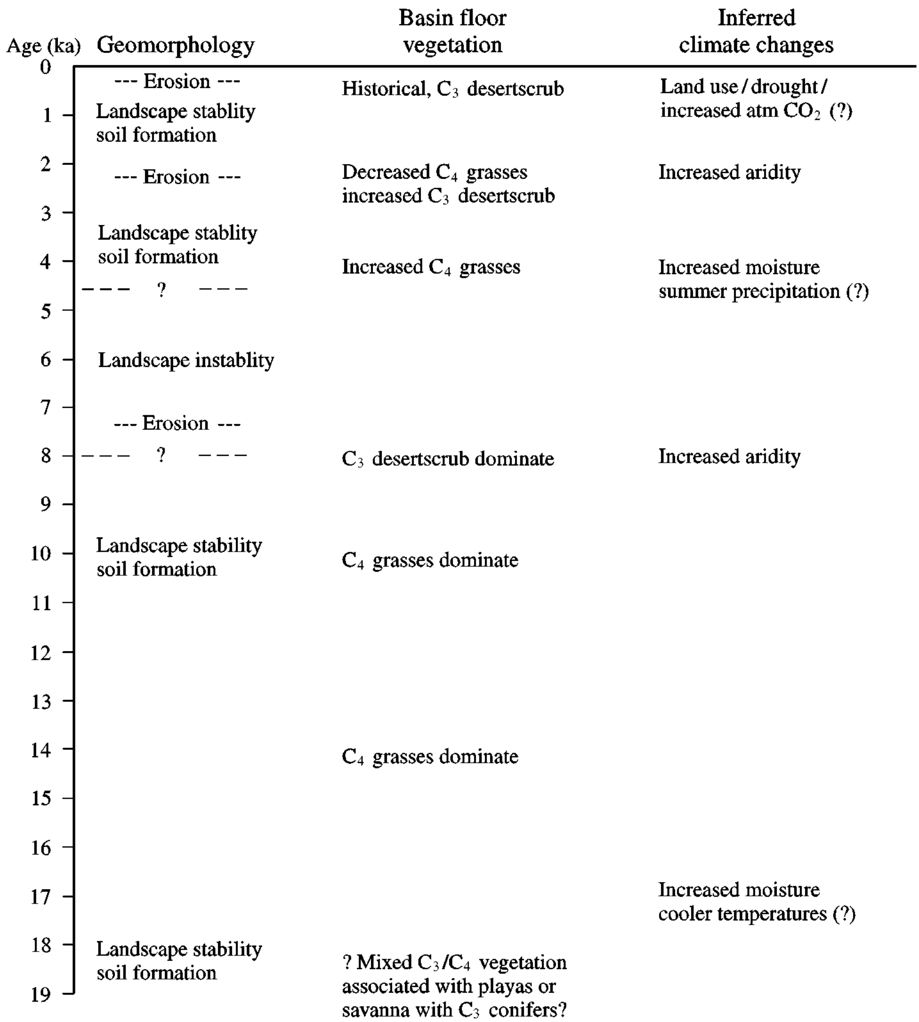

Figure 6. Interpreted geomorphic, vegetation, and climate changes in the lower elevations of the northern Chihuahuan Desert during the late Pleistocene and Holocene.

this vegetational change was not controlled by landscape position, but is found regionally in all environments: erosion along alluvial fans and eolian basin floors, coupled and aggredation along the Rio Grande. This shift in carbonate $\delta^{13}C$ values is synchronous with a period of cooling in the North Atlantic documented in ice core data (Alley *et al*., 1997). Climate models and field data suggest that cooling of the north Atlantic can lead to increased aridity in the south-western United States (Benson *et al*., 1997). Following this period of increased aridity, at approximately 4 ka it is suggested that C_4 grasses increased in abundance and a period of soil formation and landscape stabilization occurred (Fig. 6). This is consistent with other evidence of increased moisture regionally (see Ely, 1997). At approximately 2·2 ka, another period of aridity (although probably less severe) is indicated by erosion and subsequent deposition along the alluvial fans and within the eolian basin floors. Only one trench contained pedogenic carbonate this young, but it supports the geomorphic evidence and shows a shift to more depleted carbonate $\delta^{13}C$ values, indicating increased C_3 desert-scrub (Fig. 3(g)). Packrat midden studies in this region also show vegetational changes at approximately 7–9 ka, 4 ka, and 2·2 ka (Van Devender, 1990; Van Devender, 1995). Although the packrat midden data indicate different vegetational communities than the isotopic data in this study, the differences are mostly consistent with topographically controlled microclimates found today in the Chihuahuan Desert. Therefore, all available methods: soil isotopes, palynology, packrat middens, and geomorphology, should be used together whenever possible to infer past environmental conditions.

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