Palaeogeography, Palaeoclimatology, Palaeoecology 305 (2011) 65–74

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Plio-Pleistocene climate change and timing of Peninsular Ranges uplift in southern California: Evidence from paleosols and stable isotopes in the Fish Creek–Vallecito basin

Thomas C. Peryam *, Rebecca J. Dorsey, Ilya Bindeman

Department of Geological Sciences, 1272 University of Oregon, Eugene, Oregon, 97403, USA

ARTICLE INFO

Article history:
Received 28 April 2010
Received in revised form 8 February 2011
Accepted 20 February 2011
Available online 24 February 2011

Keywords:
Stable isotopes
Pliocene
Pleistocene
Climate
Southern California
Paleosols
Peninsular ranges

ABSTRACT

Abundant Plio-Pleistocene paleosols in the Fish Creek–Vallecito basin record the effects of late Neogene global climate change on inland southern California. Analysis of 82 paleosol horizons ranging in age from 3.9 to 0.7 Ma reveals two primary populations: vertic paleosols with abundant mud cracks and calcic paleosols with pronounced calcite accumulation zones. Vertic paleosols are dominant in older deposits but disappear from the stratigraphic record by 2.8 Ma, after which point calcic paleosols are nearly the only paleosol type present. Pedogenic carbonate nodules from 47 horizons were analyzed for oxygen and carbon isotopic compositions. In late Pliocene time carbonate $\delta^{13}C$ values become depleted, from an average of −5.1‰ between 3.9 and 3.5 Ma to −7.3‰ (VPDB) between 2.75 and 2.25 Ma, recording an increase in C3 plants at the expense of C4 grasses. This finding suggests that summer precipitation decreased in the study area from 3.8 to 2.5 Ma, possibly due to a weakening of the summer monsoon. The absence of vertic paleosols in post-2.8 Ma deposits supports this hypothesis. The increase in abundance of calcic paleosols through time suggests a long-term increase in aridity. A gradual enrichment of about 2‰ in $\delta^{18}O$ values from 3.9 to 0.7 Ma also likely resulted from increased aridification and evaporative enrichment of soil water. Our findings suggest that global cooling in late Pliocene time resulted in increased aridity in southern California due to decreased monsoonal activity and the end of persistent El Niño conditions in the Pacific Ocean. The observed enrichment in $\delta^{18}O$ in the Fish Creek–Vallecito basin is opposite the change that would be produced by the onset of a rain shadow, suggesting that significant uplift of the Peninsular Ranges occurred before 3.8 Ma.

1. Introduction

One of the most recent large climate changes in Earth's history took place during Pliocene to Pleistocene time, when early Pliocene warmth was replaced by a cooler and strongly variable late Pliocene to Pleistocene climate regime marked by the onset of Northern Hemisphere glaciation (e.g., Haug et al., 2001; Zachos et al., 2001; Ravelo et al., 2004; Haug et al., 2005; Lisiecki and Raymo, 2005). The Pliocene warm period is the most recent period of sustained global warmth and is considered a potential analogue for future climate (IPCC, 2007). Thus studies of Plio-Pleistocene climate change and its effects on local weather patterns can provide useful insights that aid in predicting future climate change. Despite previous work that reconstructed Late Tertiary climate change in the western U.S. (Smith, 1984; Smith et al., 1993), there is little information about this period due to poor exposure and limited age controls in Plio-Pleistocene deposits.

Paleosols exposed in deposits of the Fish Creek–Vallecito Basin of southern California provide a unique terrestrial record of continental climate conditions during the transition from early Pliocene warmth to Plio-Pleistocene glaciation. There, a 5.5 km thick Miocene to Pleistocene sedimentary section has been uplifted, tilted and exposed as a result of motion on young strike–slip faults (Dorsey et al., 2011). Rapid sedimentation and recently-published magnetostratigraphic dating enable high-resolution age determination of abundant paleosol horizons. Useful paleoclimatic and paleoecological information can be extracted from paleosol characteristics and stable isotope values of pedogenic carbonate (e.g., Cerling, 1984; Cerling et al., 1989; Quade et al., 1995). An abundance of vertebrate and invertebrate fossils has drawn researchers to the Fish Creek–Vallecito basin for over a century (e.g., Vaughan, 1904; Marrs, 2006), but until now there has been no detailed study of the climate proxies preserved in the paleosols of this area.

The Peninsular Ranges of southern California form the faulted western margin of the Salton Trough and currently produce a strong rain shadow affecting the Salton Trough lowlands and Imperial Valley (Fig. 1A; Minnich et al., 2000; Cerezo-Mota et al., 2006.). Understanding the evolution of this mountain range is important for reconstructing both Plio-Pleistocene climate change and the history of the Pacific–North

* Corresponding author. Tel.: +1 541 915 5549; fax: +1 541 346 4692.
E-mail addresses: tperyam@uoregon.edu (T.C. Peryam), rdorsey@uoregon.edu (R.J. Dorsey), bindeman@uoregon.edu (I. Bindeman).

0031-0182/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2011.02.014

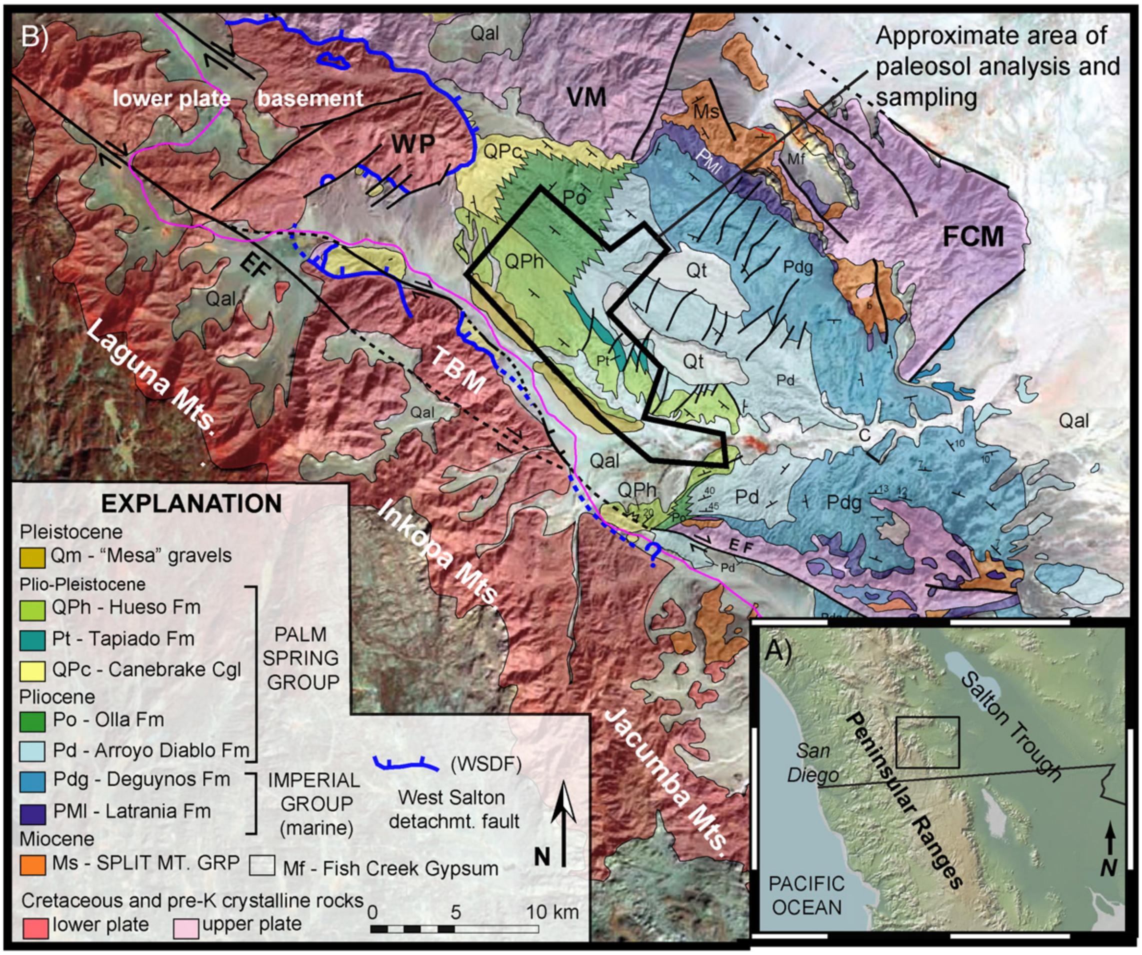

Fig. 1. A (inset) Shaded color relief map of southern California and NW Mexico showing location of map B. B) Geologic map of the Fish Creek–Vallecito Basin and surrounding area. Southwest-dipping Plio-Pleistocene strata which are the focus of this study are well exposed in badlands in Anza–Borrego Desert State Park, California. Polygon shows approximate area of paleosol analysis and sampling. Modified from Dorsey et al. (2011).

America plate boundary. Recent work suggests that lower crustal or upper mantle processes may contribute to high topography in the Peninsular Ranges (Yang and Forsyth, 2006; Mueller et al., 2009), yet the timing of uplift is not known.

This paper presents an integrated study of proxies used to interpret changes in Pliocene to Pleistocene paleoclimate. We use paleosol data and stable-isotope analyses from a well-exposed stratigraphic section to document changes in soil moisture regime and soil carbonate composition through time. We then compare this record to a previous paleoclimate study in the same section, and use these data to test hypotheses for the timing of Peninsular Ranges uplift and global climatic controls on evolution of local climate patterns in southern California.

2. Background

The Fish Creek–Vallecito basin contains a well-exposed stratigraphic record of late Miocene to early Pleistocene sedimentation along the obliquely diverging Pacific–North American plate boundary. Deposits of the Fish Creek–Vallecito basin accumulated in a supradetachment basin in the hanging wall of the West Salton detachment fault (Fig. 1B; Axen and Fletcher, 1998). A major tectonic reorganization at 1.3–1.0 Ma terminated slip on the detachment fault, initiated the San Felipe, San Jacinto and Elsinore strike–slip faults, and initiated uplift and erosion of basinal deposits (Lutz et al., 2006; Kirby et al., 2007; Steely et al., 2009). In the present-day Fish Creek–Vallecito basin a thick section (>5 km) of strata is well exposed in southwest-dipping beds along a series of dry washes and badlands.

A rich fossil record in the Fish Creek–Vallecito basin has provided evidence of large-magnitude climatic shifts in the region since mid-Pliocene time. The study area presently lies along the western margin of the Colorado Desert and averages 8–15 cm of precipitation annually. The flora of the study area in the modern interglacial period is dominated by creosote bush, saltbush and cactus scrub (Schoenherr and Burk, 2007). During Late Pleistocene glacial periods, the region had widespread Juniper scrub (Van Devender, 1990). These xeric floras are in contrast to fossil floral assemblages from the Pliocene Arroyo Diablo Formation that contain abundant hardwoods, palms and conifers, suggesting a wet and temperate climate in mid-Pliocene time with rainfall of 38–62 cm (Remeika, 2006). Plant fossils are absent in the Plio-Pleistocene deposits of the Tapiado and Hueso formations (Fig. 2), but faunal evidence suggests a shift to a cooler but still wet environment during late Pliocene to early Pleistocene time (Howard, 1963; Cassiliano, 1994; Jolly, 2000; Gensler et al., 2006; White et al., 2006). In contrast, ostracode assemblages from lacustrine deposits in the Tapiado Formation suggest that the region was warm with tropically influenced precipitation throughout most of the late Pliocene, with an increase in aridity circa 2.0 Ma (Cosma, 2002a). Brogenski (2001) interpreted enrichment in $\delta^{18}O$ in fossil horse teeth at circa 2.3 Ma to record a change from a cool and wet climate to one that was warmer and drier, possibly due to increased Pacific Ocean upwelling along the coast of California (Brogenski, 2001; Spero et al., 2003).

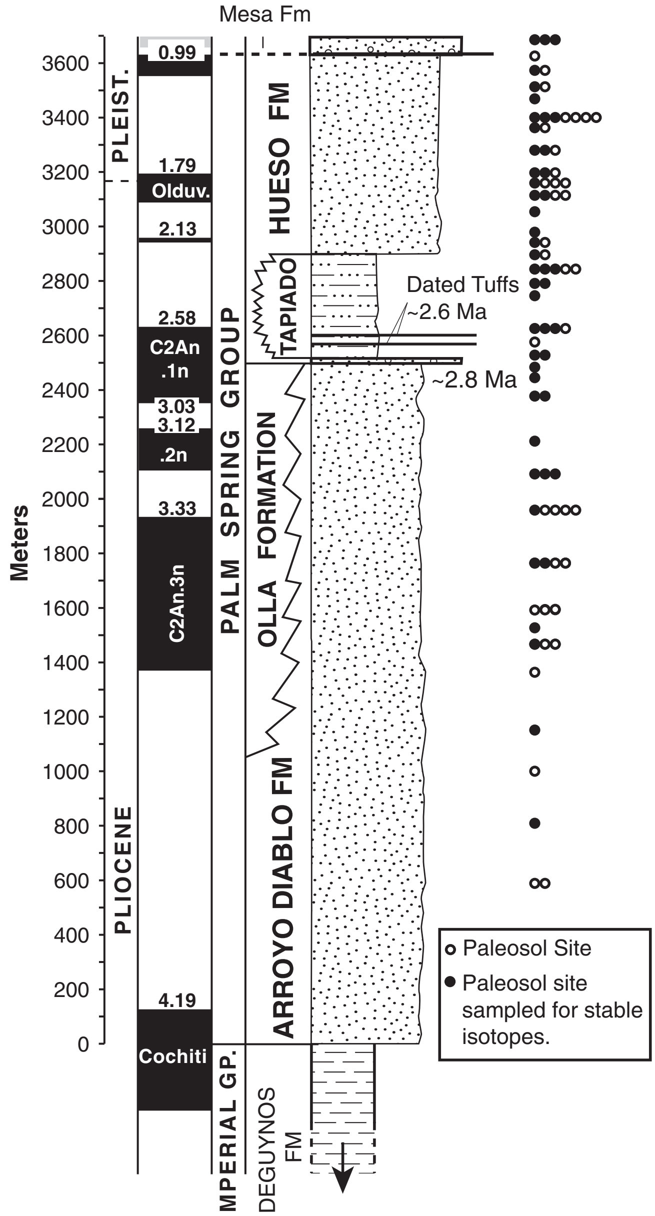

Fig. 2. Generalized stratigraphic column of the Palm Spring Group in the Fish Creek–Vallecito Basin, modified from Dorsey et al. (2011), showing approximate stratigraphic position of paleosols analyzed for this study.

In addition to uncertainty about paleoclimate evolution, the timing of uplift in the Peninsular Ranges uplift is not well understood. The current configuration of the Peninsular Ranges as a topographic boundary must post-date Eocene deposition of the Sonora-derived Poway Conglomerate along coastal California (Abbot and Smith, 1989). Late Miocene initiation of the West Salton detachment fault likely resulted in uplift of the footwall, including the Peninsular Ranges (Axen and Fletcher, 1998). Recent work indicates that high topography in the Peninsular Ranges is not supported by a crustal root (Lewis et al., 2000, 2001), and is instead supported by mantle buoyancy due to either delamination of the lower crust (Yang and Forsyth, 2006) or removal of the mantle lithosphere beneath the area (Mueller et al., 2009). Mueller et al. (2009) suggested that at least some Peninsular Ranges uplift is Quaternary in age, based on modeling of uplifted marine terraces along the Pacific Coast. Cosma (2002b) interpreted changes in lacustrine ostracodes in the Fish Creek–Vallecito basin to suggest that uplift of the Peninsular Ranges and concurrent rain shadow enhancement was ongoing throughout Pliocene time, and that the range achieved something close to its current elevation by 2 Ma.

3. Approach

This paper presents and analyses three data sets: (1) paleosol morphology, (2) carbon isotopes and (3) oxygen isotopes from pedogenic carbonate. The paleoclimatic evolution of the study area is evaluated using all three of these data sets. In addition, we use oxygen isotope data to test hypotheses for Plio-Pleistocene uplift of the Peninsular Ranges and production of a rain shadow during this time.

Paleosols provide useful proxies for paleoclimatic conditions. Soil characteristics such as horizon types, stage of soil development and type of ped structures reveal significant information about the climate, precipitation and vegetation regime in which paleosols formed (e.g., Mack and James, 1994; Retallack, 1999, 2005; Sheldon and Tabor, 2009). Paleosol investigations are made even more powerful when they are incorporated into larger paleoclimatic investigations (e.g., Quade et al., 1995; Kleinert and Strecker, 2001).

Pedogenic carbonate preserves useful paleoecological information, as it precipitates in equilibrium with soil CO_2, which is itself a product of decaying vegetative material and diffusive exchange with the atmosphere (Cerling, 1984; Cerling et al., 1989; Quade et al., 1989; Fox and Koch, 2003). Trees, shrubs and cool-season grasses utilize the C3 photosynthetic pathway and had an average, preindustrial $\delta^{13}C$ value of −25.5‰ VPDB (Fox and Koch, 2003). In relatively arid habitats (<1000 mm mean annual precipitation) C3 organic matter can be less negative, with an average $\delta^{13}C$ value of −24.6‰ VPDB (Fox and Koch, 2003). Grasses that require a warm growing season generally utilize the C4 photosynthetic pathway and had a mean, preindustrial $\delta^{13}C$ value of −11.5‰. In the late Pliocene/Early Pleistocene time period of this study, atmospheric $\delta^{13}C$ for the late Pliocene/early Pleistocene did not vary more than +/−.25‰ from the preindustrial value of −6.5‰ (Tipple et al., 2010), and thus the C3/C4 end-member values presented by Fox and Koch (2003) are used when discussing paleoecological interpretations. CAM (crasulacean acid metabolism) plants include many desert succulents, and have a $\delta^{13}C$ value intermediate between C3 and C4 plants (Farquhar et al., 1989). Diffusion kinetic effects and fractionation during calcite precipitation enrich soil carbonate by 14–17‰, but the difference in values between C3 and C4 biotas is preserved. Pedogenic carbonate in soils dominated by C4 grasses therefore has a $\delta^{13}C$ of around +2‰, while carbonate in soils dominated by C3 plants has a typical $\delta^{13}C$ of −12 to −9‰, with lighter values typical of more arid environments (Cerling, 1984; Cerling et al., 1989; Fox and Koch, 2003).

Oxygen isotopes in pedogenic carbonate provide a valuable tool for detecting ancient tectonic uplifts due to their tendency to record the effects of orographic rain shadows. Oxygen isotopes in pedogenic carbonate are well correlated with the isotopic composition of local precipitation, despite differences in temperature and pedogenic processes of carbonate formation (Cerling, 1984; Cerling and Quade, 1993). Pedogenic carbonate has been used by numerous workers to detect the timing and extent of ancient orographic events, since atmospheric water vapor becomes depleted in ^{18}O as it passes over mountain ranges (Cerling et al., 1989; Chamberlain and Poage, 2000; Kleinert and Strecker, 2001; Kent-Corson et al., 2006; Quade et al., 2007). This orographic fractionation is reflected both in soils formed at elevation and in soils formed in lee-side sedimentary basins.

The Fish Creek–Vallecito basin, located on the leeward side of the Peninsular Ranges, presently lies in a hyper-arid orographic rain shadow (mean annual precipitation = 10–15 cm). Complications related to below-cloud-base evaporation and/or mixing of water vapor sources can obscure the isotopic record of an orographic rain shadow, especially in arid environments (Blisniuk and Stern, 2005). Most modern precipitation in the study area comes from winter storms originating in the Pacific Ocean (Woodhouse, 1997; Minnich et al., 2000). The

Peninsular Ranges are oriented perpendicular to winds carrying this water vapor, and thus are a potential source of an isotopic rain shadow (Blisniuk and Stern, 2005). There is a paucity of data on the isotopic composition of meteoric precipitation in the western Salton Trough, but water vapor passing over the Peninsular Ranges is known to be isotopically depleted due to orographic effects, and groundwater in the Imperial Valley shows depleted $\delta^{18}O$ values, although these values are complicated by irrigation with water from the Colorado River (Williams and Rodoni, 1997). If significant uplift of the Peninsular Ranges occurred during late Pliocene to early Pleistocene time, the resultant creation or enhancement of a rain shadow could be reflected in $\delta^{18}O$ values from pedogenic carbonate analyzed in this study.

4. Methods

A total of 82 paleosols were surveyed in the upper non-marine ~3.2 km of the stratigraphic section in the Fish Creek–Vallecito basin (Fig. 2). Paleosols ages were assigned using the results of a new, high-resolution magnetostratigraphic study (Dorsey et al., 2011). Ages of each isotopic sample site are shown in Table 1, and the ages of each described paleosol are listed in Appendix A. Field mapping and satellite photos were used to project individual sites into the stratigraphic section of Dorsey et al. (2011), and site ages were calculated using the stratigraphic height above or below a magnetic reversal divided by the sediment accumulation rate in that part of the section. Sites situated in poorly constrained magnetic chrons or further from the paleomagnetic sampling transect are assigned higher age uncertainties than paleosols within well-constrained chrons and/or co-located with the paleomagnetic transect. The average uncertainty of sampled paleosols dated with this method is +/− 0.06 m.y. Paleosols separated from the magnetostratigraphic section by faults cannot be dated using this method and were assigned ages through stratigraphic inference with a much larger uncertainty (usually +/− 0.1–0.2 m.y.). The average sample age uncertainty for the entire dataset is +/− 0.07 m.y.

Pedogenic carbonate nodules were collected from the carbonate-accumulation (Bk) horizon of 47 paleosols. The Bk horizon is defined as the interval in which nodules or other forms of carbonate dominate the fabric of the soil profile (Soil Survey Staff, 1999). Sampled nodules range in size from 0.5 cm to 3 cm in diameter. Nodules that contain more than 5% sparry calcite as seen in thin section were not included in this study due to probable recrystallization and diagenetic contamination of isotope values. Nodules were cleaned, crushed, weighed and loaded into beakers. Beakers were flushed with helium gas in a Gasbench and then dissolved in phosphoric acid. The resulting carbon dioxide was analyzed in a MAT253 mass spectrometer at the University of Oregon Stable Isotope Lab, along with the NBS-19 carbonate standard ($\delta^{13}C = 1.95‰$ and $\delta^{18}O = -2.2‰$). Stable isotope ratios are reported relative to the Vienna PeeDee Belemnite (VPDB) scale. Analytical errors in Table 1 are reported as two standard deviations of repeated measurements of the same gas. The mean sample uncertainties are ±0.09‰ for $\delta^{13}C$, and ±0.12‰ for $\delta^{18}O$. In order to test for reproducibility, a subset of five nodules were subsampled and analyzed separately. The resulting values showed an average range of 0.26‰ for $\delta^{13}C$ and 0.44‰ for $\delta^{18}O$ (Appendix B), far smaller than the overall range of isotope ratios in those two systems. These multiple analyses are reported as averaged values and are marked with an asterisk in Table 1.

5. Results

5.1. Paleosols

Paleosols in the Fish Creek–Vallecito basin are divided into two primary populations: vertic and calcic. Vertic paleosols are found exclusively in deposits older than 2.8 Ma whereas calcic paleosols are found throughout the studied section (Fig. 3). Vertic paleosols are the dominant paleosol type in deposits between 4.0 and 3.0 Ma and decrease in abundance over time before vanishing from the stratigraphic record at about 2.8 Ma (Fig. 3). Calcic paleosols are nearly the only paleosol type present in strata younger than 2.8 Ma.

Table 1
Age and isotopic value of pedogenic carbonate samples.

Sample	Age (Ma)	δ13C (‰)	δ18O (‰)	UTM (NAD 83) Northing	UTM (NAD 83) Easting
P09-AB-35	0.75 ± 0.25	−4.77 ± 0.04	−8.43 ± 0.08	576493	3637260
P08-AB-23	0.75 ± 0.25	−5.27 ± 0.13	−8.6 ± 0.13	569852	3645422
P08-AB-22b	0.75 ± 0.25	−6.74 ± 0.14	−8.34 ± 0.24	569749	3645364
P08-AB-19	1.10 ± 0.06	−3.65 ± 0.06*	−8.24 ± 0.07*	571549	3643778
P08-AB-18	1.21 ± 0.07	−6.03 ± 0.12	−8.92 ± 0.11	571644	3644022
P08-AB-25	1.27 ± 0.06	−6.37 ± 0.08	−8.69 ± 0.069	571586	3644233
P08-AB-17	1.42 ± 0.05	−7.27 ± 0.13	−10.73 ± 0.25	571920	3644180
P09-AB-13	1.43 ± 0.06	−6.39 ± 0.06	−8.57 ± 0.08	571897	3644397
P09-AB-14	1.46 ± 0.06	−2.38 ± 0.04	−8.71 ± 0.08	571785	3644605
P08-AB-15	1.50 ± 0.05	−4.68 ± 0.13	−9.33 ± 0.29	571959	3644440
P08-AB-16	1.68 ± 0.05	−3.46 ± 0.12*	−9.84 ± 0.13*	572034	3644696
P09-AB-42	1.69 ± 0.04	−6.25 ± 0.07	−8.86 ± 0.11	573375	3643289
P08-AB-13	1.79 ± 0.03	−7.99 ± 0.13	−10.68 ± 0.16	572768	3644227
P09-AB-38	1.80 ± 0.03	−6.9 ± 0.06	−9.22 ± 0.06	573501	3643351
P08-AB-14	1.84 ± 0.03	−6.77 ± 0.1	−9.55 ± 0.21	572048	3644953
P08-AB-12	1.92 ± 0.06	−7.4 ± 0.08	−7.96 ± 0.13	573178	3644118
P08-AB-11	1.94 ± 0.03	−4.08 ± 0.1	−9.37 ± 0.02	573660	3643494
P09-AB-32	2.03 ± 0.04	−8.94 ± 0.12	−9.75 ± 0.1	570453	3647406
P09-AB-34	2.11 ± 0.09	−7.11 ± 0.1	−8.47 ± 0.05	574750	3642488
P09-AB-28	2.15 ± 0.04	−9.03 ± 0.07	−9.89 ± 0.12	572446	3645522
P09-AB-33	2.19 ± 0.06	−6 ± 0.09	−8.41 ± 0.06	575075	3642367
P08-AB-9	2.25 ± 0.04	−8.07 ± 0.1	−10.16 ± 0.26	572616	3645624
P09-AB-26	2.28 ± 0.04	−5.25 ± 0.07	−7.98 ± 0.07	572570	3645740
P09-AB-27	2.28 ± 0.04	−6.91 ± 0.12	−8.03 ± 0.09	572570	3645740
P09-AB-29	2.32 ± 0.03	−7.16 ± 0.05	−9.19 ± 0.07	572418	3645994
P09-AB-25	2.34 ± 0.02	−6.52 ± 0.09	−8.87 ± 0.09	572995	3645404
P08-AB-7	2.39 ± 0.02	−6.2 ± 0.13	−9.15 ± 0.27	572797	3645966
P09-AB-12	2.61 ± 0.1	−8.42 ± 0.07	−9.66 ± 0.12	572626	3646605
P09-AB-11	2.62 ± 0.1	−7.15 ± 0.15	−9.03 ± 0.06	572580	3646685
P08-AB-6	2.62 ± 0.1	−10.4 ± 0.12	−12.35 ± 0.15	572580	3646685
P08-AB-5	2.76 ± 0.07	−5.6 ± 0.11	−10.61 ± 0.13	572614	3646874
P08-AB-22	2.80 ± 0.2	−5.7 ± 0.1	−8.31 ± 0.11	577710	3641466
P09-AB-9	2.85 ± 0.04	−4.35 ± 0.1	−9.8 ± 0.23	572629	3647017
P09-AB-41	2.90 ± 0.1	−4.79 ± 0.07	−8.51 ± 0.11	578324	3640106
P09-AB-23	3.00 ± 0.2	−8.35 ± 0.11	−9.54 ± 0.05	578194	3640979
P09-AB-20	3.00 ± 0.2	−7.01 ± 0.05	−8.73 ± 0.04	582077	3635946
P08-AB-31	3.18 ± 0.06	−3.27 ± 0.07*	−9.6 ± 0.9*	573630	3646976
P08-AB-4	3.23 ± 0.05	−5.03 ± 0.09	−10.3 ± 0.15	573029	3647519
P09-AB-6	3.25 ± 0.03	−5.19 ± 0.07	−8.72 ± 0.1	572859	3647816
P09-AB-7	3.25 ± 0.03	−4.96 ± 0.07	−8.53 ± 0.11	572859	3647816
P09-AB-31	3.30 ± 0.01	−9.33 ± 0.08	−9.84 ± 0.07	572287	364883
P09-AB-37	3.40 ± 0.15	−4.11 ± 0.05	−9.37 ± 0.1	572195	3649457
P08-AB-3	3.41 ± 0.01	−9.04 ± 0.13*	−10.19 ± 0.16*	573266	3648186
P08-AB-28	3.53 ± 0.01	−6.14 ± 0.14	−10.39 ± 0.26	573613	3648535
P09-AB-39	3.55 ± 0.15	−7.2 ± 0.11	−9.94 ± 0.07	570253	3651313
P08-AB-26	3.70 ± 0.01	−4.23 ± 0.1	−11.02 ± 0.13	574286	3649029
P09-AB-40	3.83 ± 0.01	−2.78 ± 0.07	−10.48 ± 0.08	576716	3647197

* Asterisk denotes isotope value averaged from multiple analyses of the same sample.

Vertic paleosols contain many features produced by shrinking and swelling of clay minerals during soil formation. Vertic paleosols in the studied section exhibit deeply-penetrating soil cracks, lenticular to angular peds with clay cutans, and well-developed slickensides (Fig. 4). Vertic paleosols in this section are relatively thin (<1 m thick) and lack some of the features commonly associated with true Vertisols, such as gilgai microrelief (Dudal and Eswaran, 1988; Soil Survey Staff, 1999), and are best understood as Vertic Inceptisols rather than true Vertisols. Variations of vertic paleosols include clayey paleosols with slickensides and angular peds but no soil cracks, as well as clayey cracked paleosols with a surface gleyed horizon. Dispersed, thin (3–7 cm thick) zones of calcite enrichment are present near the base of some vertic paleosols (Fig. 4). These horizons may represent very weakly-developed soil carbonate (Bk) horizons (Stage I of Machette, 1985), although their very

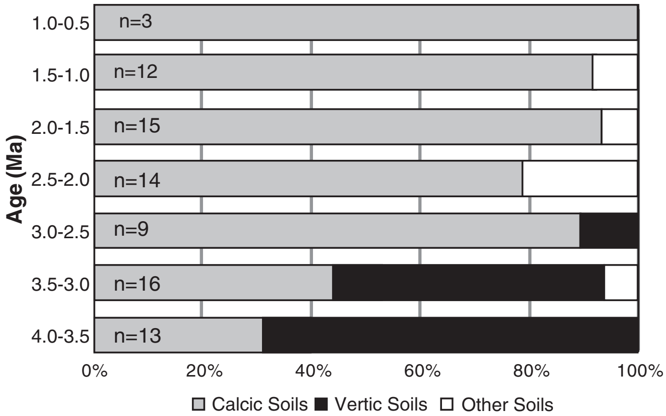

Fig. 3. Relative abundance of paleosol types as a function of age, grouped into 0.5-m.y. bins. Vertic soils, which are dominant in the interval 4.0 to 3.0 Ma, decrease in abundance before disappearing from the stratigraphic record by about 2.8 Ma.

thin nature suggests that the calcite enrichment may be non-pedogenic. Calcite from these zones was not included in the stable isotope analyses.

Calcic paleosols are characterized by the presence of a prominent Bk horizon (Fig. 5). Calcic paleosols in the Fish Creek–Vallecito basin have thin to non-existent A horizons and shallow Bk horizons. Some A horizons contain visible root traces and small, 1–2 cm diameter burrows. Bk horizons range from a very faint horizon of calcite enrichment to a well-developed zone of intergrown pedogenic carbonate nodules (stage I to stage III calcic soils of Machette (1985), with most calcic paleosols exhibiting 0.5–4 cm diameter carbonate nodules in a non-calcareous matrix (stage II calcic soils). Carbonate nodules have displacive, calciasepic fabrics and range from orthic to disorthic (e.g., Wieder and Yaalon, 1974). Framework grains are present in nodules to varying degrees, with embayed quartz grains most common. Feldspar and biotite are present within nodules, and are more pervasively replaced than quartz. Evidence for scouring and erosion of surface horizons is common in calcic paleosols, and in some cases all material overlying the Bk has been removed prior to deposition of overlying sediment. In other paleosols, multiple Bk horizons overlie each other due to soil overprinting (Fig. 5A). In the small subset of paleosols ($n=19$) where depth to the Bk horizon can be measured with confidence Bk horizons are typically shallow, with an average undecompacted depth of 31 cm (Fig. 6). Most calcic paleosols lack identifiable peds, although poorly-developed blocky peds are sometimes present. Calcic paleosols are interpreted as Calcids (i.e. Calcic Aridisols; Soil Survey Staff, 1999). Variations among calcic paleosols include paleosols with substantially thicker and deeper Bk horizons as well as calcic paleosols with a surface gley horizon.

Other paleosol types present in the studied section include poorly developed Inceptisols and deep calcic paleosols developed on lacustrine limestone. Inceptisols are identified by the presence of root traces as well as weakly developed cambic horizons. These paleosols are uncommon and are found throughout the stratigraphic column.

5.2. Stable isotopes from pedogenic carbonate

The results of analyses of 47 pedogenic carbonate horizons are listed in Table 1 and plotted against age in Fig. 7. The data show large scatter with an overall depletion in $\delta^{13}C$ of about 2‰ between 3.9 and 2.0 Ma, from an average of −5.08‰ between 3.9 and 3.5 Ma to −7.34‰ between 2.75 and 2.25 Ma (Fig. 7A). After 2.5 Ma there is a minor enrichment in $\delta^{13}C$ of about 1.5‰ by the interval 1.5–1.0 Ma. Oxygen isotope values show less scatter and display a coherent slight enrichment in $\delta^{18}O$ from an average of −10.5‰ between 3.9 and 3.5 Ma to −8.4‰ between 1.0 and 0.7 Ma (Fig. 7B).

6. Discussion

6.1. Paleosol evolution

The shift from vertic to calcic paleosols is roughly coincident with progradation of the locally derived Hueso and Tapiado formations

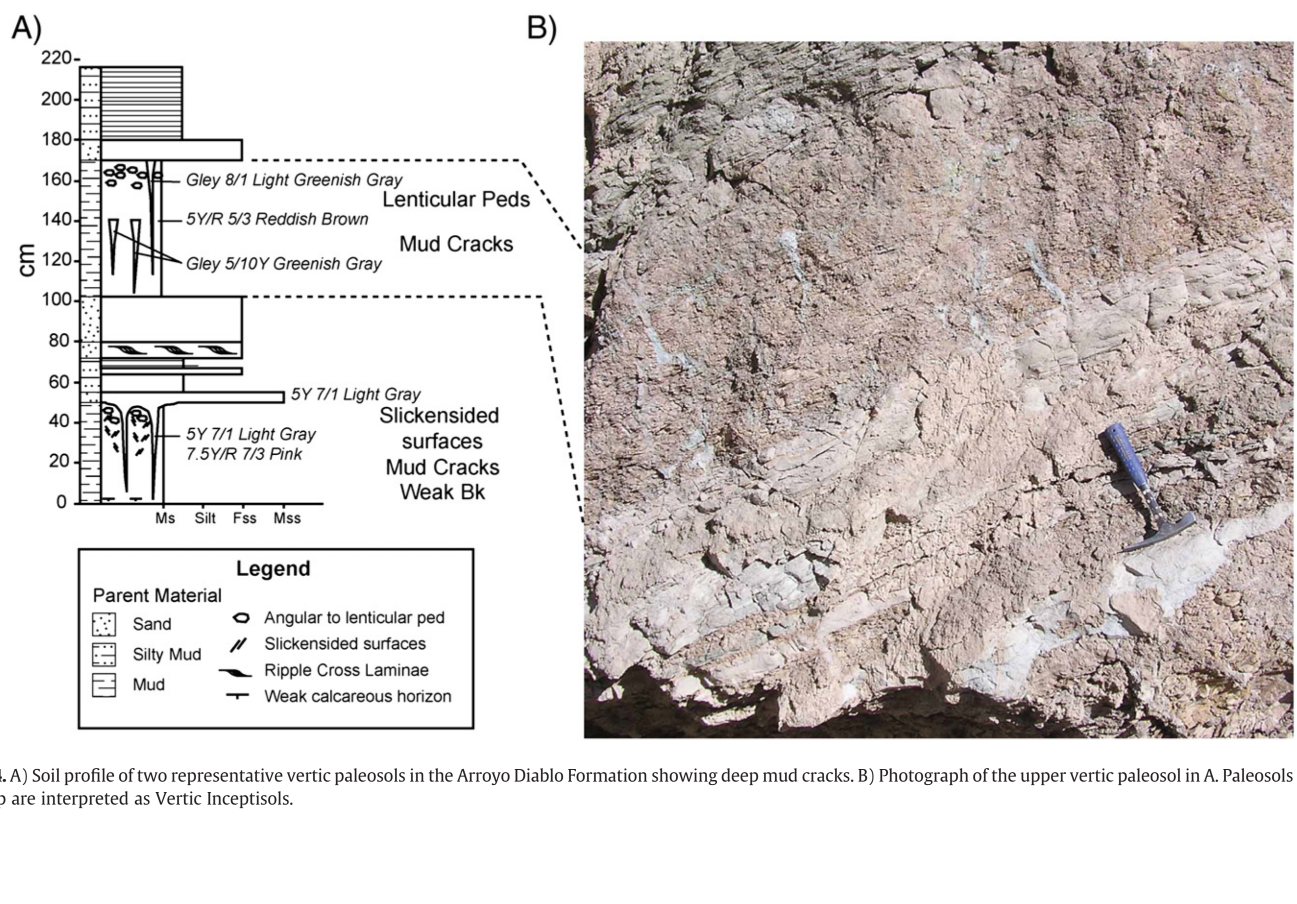

Fig. 4. A) Soil profile of two representative vertic paleosols in the Arroyo Diablo Formation showing deep mud cracks. B) Photograph of the upper vertic paleosol in A. Paleosols in this group are interpreted as Vertic Inceptisols.

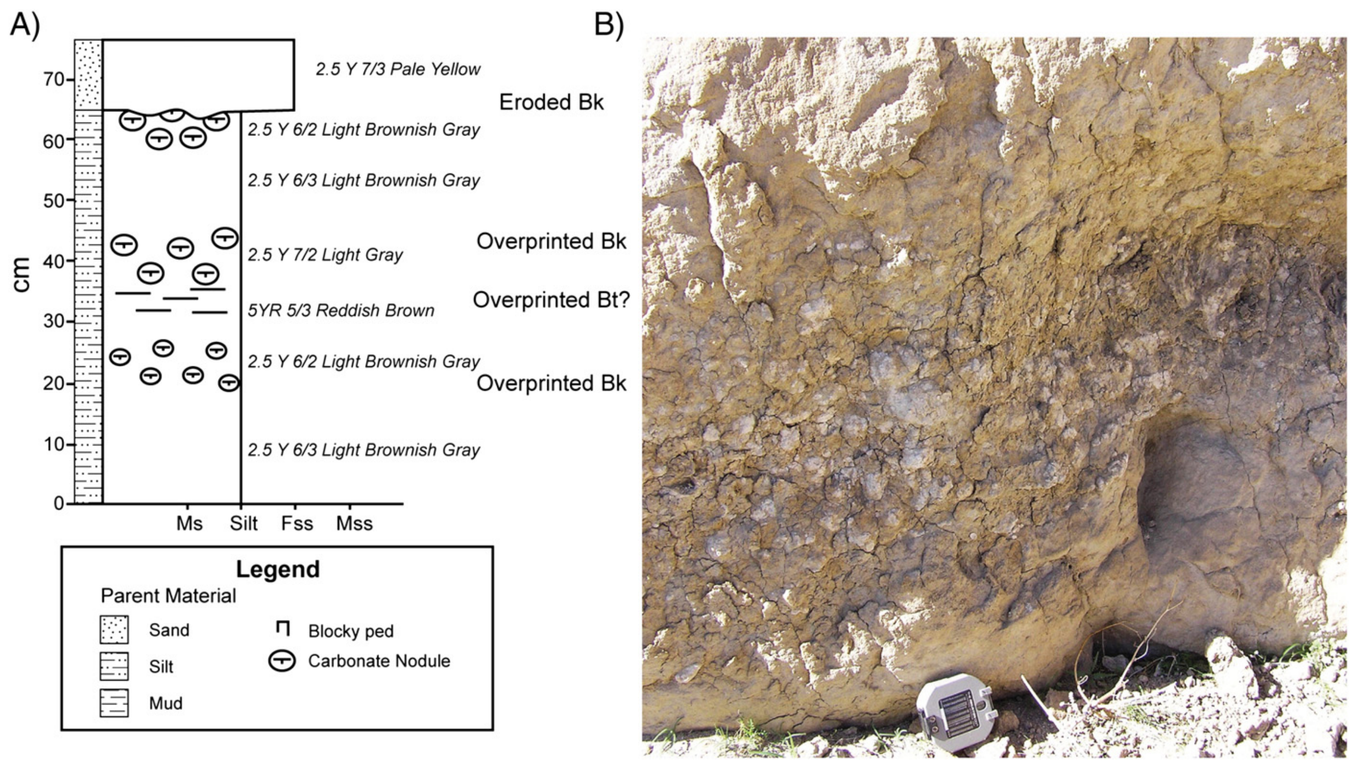

Fig. 5. Soil profiles of calcic soils showing (A) typical profile and (B) photograph of a nodular Bk horizon as commonly exposed in the Hueso Fm. Paleosols in this group are interpreted as calcic Aridisols.

(Fig. 3), although the abrupt change in sediment provenance is not itself a satisfactory explanation for the disappearance of vertic paleosols. Locally derived deposits appear suddenly in the section (Dorsey et al., 2011), whereas the disappearance of vertic paleosols was preceded by a gradual decrease spanning roughly 1 m.y. Locally-derived sediment also contains abundant swelling clays, in spite of the overall coarser nature of these deposits (Carey, 1976). We infer that the decrease and demise of vertic paleosols and their replacement by calcic paleosols was driven by a decrease in overall seasonality of rainfall. Vertic soils form in areas where seasonal rainfall leads to repeated cycles of water-saturation and desiccation (Dudal and Eswaran, 1988; Driese and Mora, 1993; Caudill et al., 1996). Soils that are either continually moist or never water-saturated will not undergo the shrinking and swelling of clay minerals that create the features associated with vertic soils (Soil Survey Staff, 1999).

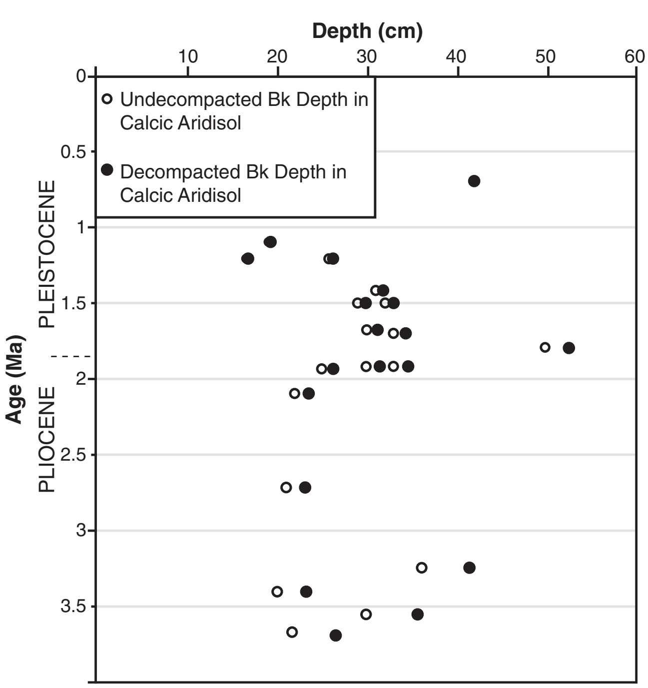

Fig. 6. Depth to calcic enrichment (Bk) horizon in calcic Aridisols as a function of age. Data shown represent subset of 19 paleosols with identifiable, un-eroded surface horizons. Decompacted depths to Bk calculated using the methodology of Sheldon and Retallack (2001).

Calcic Aridisols with shallow Bk horizons form in areas of low to moderate precipitation (Soil Survey Staff, 1999; Retallack, 2005), whereas vertic soils are found in sub-humid to semiarid climate zones (Caudill et al., 1996). We infer that a climate regime dominated by highly seasonal precipitation caused periodic water-logging and vertic soil formation during middle to late Pliocene time. The cessation or weakening of seasonal precipitation from 3.7 to 2.8 Ma likely caused the decrease and end of vertic paleosol formation by 2.8 Ma. Concurrent with and possibly resulting from this reduction in seasonality, the increased abundance and eventual dominance of calcic Aridisols shows that aridity increased over time and became the dominant climate condition by about 2.5–3.0 Ma. The average decompacted depth to Bk horizon of 31 cm (Fig. 6) corresponds to a mean annual precipitation of 359 ± 147 mm in modern soils (Retallack, 2005).

6.2. Carbon isotopes

A reduction in seasonality of precipitation is also suggested by the carbon-isotope data, which show a depletion in $\delta^{13}C$ values from about 3.9 to 2.5 Ma (Fig. 7A). This trend suggests a possible increase in abundance of C3 plants at the expense of C4 grasses. Because C4 grasses tend to grow in areas with abundant warm-season precipitation (Sage et al., 1999), our data suggest a decrease in summer

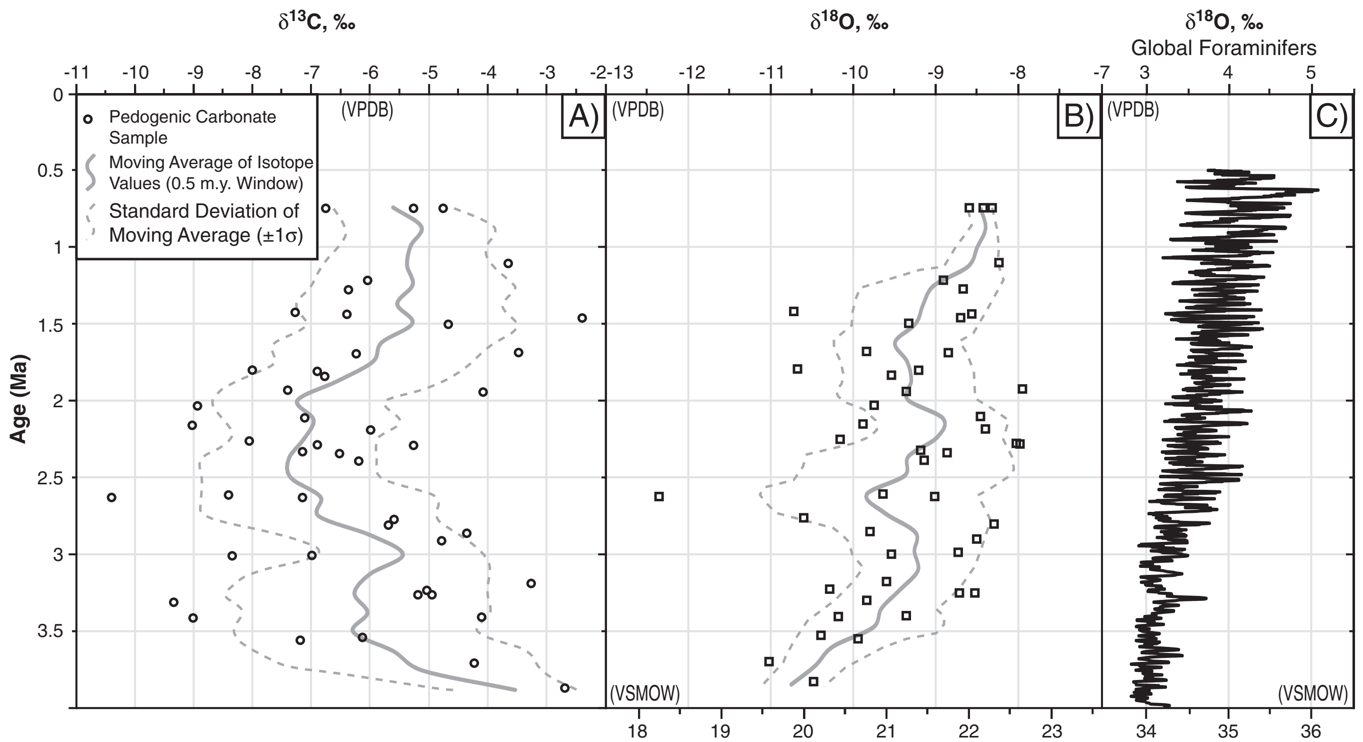

Fig. 7. (A) Carbon and (B) oxygen isotope ratios of pedogenic carbonate as a function of age. Open circles show data for individual samples. Line shows 0.5 m.y. moving average of isotopic values. (C) δ^{18}O values for global benthic foraminifers compiled by Lisiecki and Raymo (2005).

precipitation and a shift toward a Mediterranean-type climate with winter precipitation and summer drought. This shift does not necessarily require cooling of the area; it instead suggests that more vegetation growth took place during the cool season rather than the warm season, consistent with a reduction in summer precipitation and overall decrease in seasonality. This finding is consistent with paleobotanical evidence from fossil assemblages, which suggest that the present-day winter-wet Mediterranean-type climate conditions developed in southern California between middle Pliocene and early Pleistocene time (Axelrod, 1973; Graham, 1999). Regional cooling is a possible additional cause of this proposed vegetation shift, as the timing of the δ^{13}C depletion generally corresponds with global cooling at the onset of northern hemisphere glaciations (Raymo, 1994; Zachos et al., 2001; Ravelo et al., 2004).

An enrichment in δ^{13}C of about 1.5‰ from ca. 2.5 to 1.0 Ma probably reflects increasing aridity and a decrease in soil productivity. Ongoing aridification, as suggested by the paleosol record, likely led to an overall decrease in soil productivity. Low rates of soil productivity can result in infiltration of atmospheric CO_2 into the soil, which has the effect of enriching soil CO_2 in δ^{13}C (Amundson et al., 1988; Stevenson et al., 2005; Breecker et al., 2009). Enrichment of δ^{13}C between 2.5 and 1.0 Ma may also reflect an increase in the abundance of desert succulents using the CAM photosynthetic pathway.

It is possible that all observed variations in pedogenic carbonate δ^{13}C reported here were solely driven by changes in soil productivity. This possibility must be considered in light of observed shallow Bk formation in paleosols in the study area (Fig. 6). In this interpretation, depletion of δ^{13}C in paleosol carbonate between ~3.8 and 2.5 Ma would reflect increasing soil productivity, probably related to increasing precipitation and a corresponding decreasing atmospheric input. This possibility is inconsistent with changes in paleosol morphology documented in this study. While we favor the interpretation that δ^{13}C depletion between 3.9 and 2.5 Ma was driven by vegetative changes, any explanation for the observed variation in carbon-isotope data is at this time non-unique.

6.3. Oxygen isotopes

Large scatter in measured δ^{18}O ratios (Fig. 7B) suggests large variation in both precipitation and local evaporation regime. Milankovitch-scale climate variations (e.g., Lisiecki and Raymo, 2005; Fig. 7C) likely affected local isotopic δ^{18}O ratios of meteoric precipitation through temperature effects on fractionation. Shifts in the δ^{18}O composition of the oceanic source of meteoric precipitation may have varied by as much as 1‰ between glacial and interglacial periods (Schrag et al., 1996). Similarly, alternating periods of relative humidity and aridity may have altered the evaporative regime of soil water, driving variation in pedogenic carbonate δ^{18}O (Cerling and Quade, 1993; Hsieh et al., 1998). Glacial–interglacial scale variation in pedogenic carbonate δ^{18}O can be up to 4‰ (Retallack et al., 2004). The pedogenic carbonate nodules studied here took 100's to 1,000's of years to form (Machette, 1985). This time-averaging in the carbonate isotopic record and the $\pm$70 k.y. sample age uncertainty make correlation of individual paleosol profiles to specific glacial or interglacial periods impossible. Long-term trends are, however, significant despite the scatter in the isotopic record. In particular, oxygen isotopes from pedogenic carbonate in the Fish Creek–Vallecito basin record a systematic long-term enrichment in soil waters during late Pliocene and early Pleistocene time.

Enrichment of oxygen isotopes in the study area (Fig. 7B) was likely driven by long-term aridification. Aridification drives evaporation of soil water, resulting in increased fractionation and an increase in δ^{18}O (Cerling and Quade, 1993; Hsieh et al., 1998). This interpretation is consistent with and supported by similar indications of gradual aridification from paleosol characteristics. The enrichment in oxygen isotopes reported here corresponds to a long-term enrichment of global seawater δ^{18}O of ~1‰ (Fig. 7C; Lisiecki and Raymo, 2005). However, δ^{18}O in pedogenic carbonate in the section increased by a greater amount (2–3‰) during the same time interval, further suggesting a local climate influence.

Alternatively, it is possible that the enrichment in δ^{18}O values could record a shift to a warmer, more tropically derived water vapor source.

We do not favor this alternative. Climate conditions that create warmer water vapor sources in southern California precipitation, such as warm El Niño Southern Oscillation (ENSO) events, are thought to have decreased after 2.8 Ma (Molnar and Cane, 2002; Wara et al., 2005).

6.4. Paleoclimate evolution of Southern California

Weakening of the North American monsoon is the most likely mechanism to explain reduced seasonality and increased aridity in the Fish Creek–Vallecito basin from middle Pliocene to early Pleistocene time. Summer precipitation in southwestern North America comes primarily in the form of the North American monsoon (Adams and Comrie, 1997). The monsoon in this region originates when water vapor advected from the Gulf of California is drawn eastward and northward by a thermal low over the southern Cordillera (Higgins et al., 1997). The study area presently lies near the northwestern limit of the present-day North American monsoon (Fig. 8; Mitchell, 1976; Higgins et al., 1999). Higher global temperatures during Pliocene time (Raymo et al., 1996; Haywood and Valdes, 2004) likely contributed to higher-than-modern sea surface temperatures in the Gulf of California, which have been shown to increase advection of moisture into the North American Monsoon (Mitchell et al., 2002). Higher-than-modern middle Pliocene temperatures may have also created a larger than present-day summer thermal low in southwestern North America, drawing more large storms into the area. Large storms would have brought higher-than-modern annual precipitation, greater seasonal water-logging of soils and resultant vertic paleosol formation, and would have contributed to a summer growing season of warm-season grasses. The combination of late Pliocene cooling of the coastal Pacific Ocean (Dekens et al., 2007) and southward deflection of the westerly jet stream due to global cooling and growth of the Laurentide Ice Sheet (Spaulding, 1991) likely caused a decrease in summer precipitation in the study area. Dextral motion on the San Andreas fault system has transl357ated the study area ~200 km NNW since 4 Ma (Oskin and Stock, 2003). This tectonic transport could also have contributed to decreasing seasonality by moving the study area away from the area of maximum monsoon influence. The remaining winter precipitation maintained a cool winter growing season, but precipitation was of insufficient concentration and/or abundance to fully waterlog soils and contribute to vertic paleosol formation.

Several workers have suggested that a virtually permanent ENSO condition existed prior to roughly 2.8 Ma (Molnar and Cane, 2002; Wara et al., 2005). In this case, southern California would have experienced abundant winter precipitation during early to mid-Pliocene time (Woodhouse, 1997; Cayan et al., 1998; Mo and Higgins, 1998). We suggest that a decrease in monsoonal precipitation from 3.8 to 2.5 Ma was coupled with a decrease in winter precipitation due to the end of persistent ENSO conditions. The data presented above support a hypothesis in which an increase in the relative abundance of winter precipitation was coupled with an overall decrease in mean annual precipitation. The data record progressive climate change from 3.8 to 0.75 Ma. This finding is consistent with recent paleoclimate studies that document gradual, long-term global cooling and climate reorganization beginning as early as 4.0 to 3.6 Ma (Ravelo et al., 2004; Mundelsee and Raymo, 2005; Dekens et al., 2007).

6.5. Comparison with previous studies

The results of this study are broadly consistent with those of previous paleoclimatic investigations of the Fish Creek–Vallecito basin area. The middle Pliocene Carrizo Local Flora was wet-adapted (Remeika, 2006), consistent with our interpretation of a relatively wet paleoclimate during that time interval. A stable-isotope study of fossil horse teeth in the same stratigraphic section analyzed for this study found that $\delta^{13}C$ values in horse teeth became depleted over the time interval 3–0.8 Ma, while $\delta^{18}O$ was enriched over the same interval (Brogenski, 2001; Spero et al., 2003). Increasing aridity in the latest Pliocene is supported by faunal evidence from lacustrine ostracodes (Cosma, 2002a). Microfossils of small

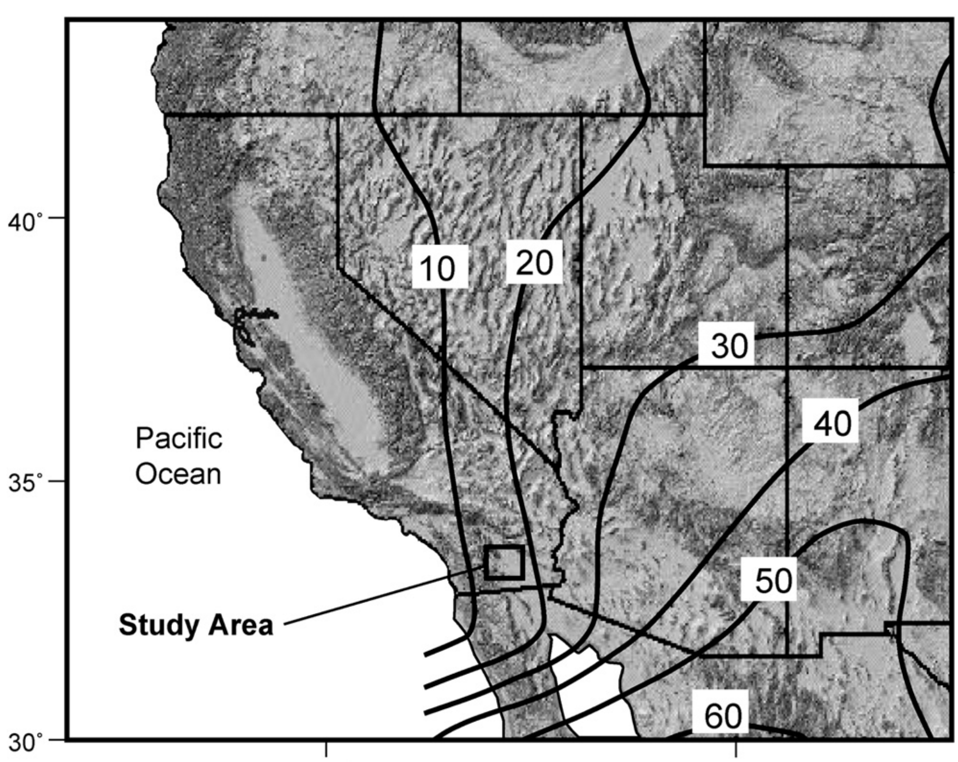

Fig. 8. Map showing the distribution of monsoonal precipitation across southwestern North America (modified from Higgins et al., 1999). Contour lines show the percentage of annual precipitation provided by the North American monsoon in July, August and September for the period 1963–1988.

reptiles and mammals in the Hueso and Tapiado formations support the interpretation of a warm, wet middle Pliocene climate that gradually became dryer post-2.8 Ma (Gensler et al., 2006; White et al., 2006). Because prior paleoclimatic studies of the Fish Creek–Vallecito basin predate a recent high-precision magnetostratigraphic study (Dorsey et al., 2011), previous interpretations will need to be re-evaluated in light of the new age controls.

6.6. Timing of Peninsular Ranges uplift

Our results show that the Peninsular Ranges of southern California likely did not undergo significant uplift between 0.75 and 3.8 Ma. In fact, our finding of enrichment in $\delta^{18}O$ through time is opposite of the change that would be produced by the onset of a rain shadow in the study area. The data therefore imply that significant uplift of the Peninsular Ranges probably occurred before 3.7 Ma or after 1 Ma, or perhaps took place in two stages before 3.7 Ma *and* after 1 Ma. This finding does not rule out regional uplift driven by progressive removal of the mantle lithosphere under the Peninsular Ranges, as hypothesized by Mueller et al. (2009). As noted by these authors, mantle-driven uplift may have raised the crest of the Peninsular Ranges by only 30 to several hundred meters, an amount that is too small to be reliably detected using oxygen isotopes.

We considered the possibility that the long-term aridification trend documented above resulted not from global climate change, as we propose, but rather was produced by the progressive growth of an orographic rain shadow created by uplift of the Peninsular Ranges, as has been suggested by previous workers (e.g., Cosma, 2002a; Sussman et al., 2006). In this scenario, we would infer that the observed increase in $\delta^{18}O$ which we credit to *in situ* evaporative enrichment of soil water was large enough to offset any depletion of $\delta^{18}O$ in meteoric water due to orographic isotope fractionation. We do not favor this interpretation because there is no mechanism associated with Peninsular Ranges uplift that could explain the observed decrease in seasonality. The Gulf of California is the primary source of water vapor for monsoonal precipitation in the region (Adams and Comrie, 1997). Advection from the Gulf of California, located south of the study area, would not be affected or diminished by uplift of mountains to the west of the basin.

7. Conclusions

The results of this study show that seasonality of precipitation in the Fish Creek–Vallecito basin decreased from middle Pliocene to early Pleistocene time (~3.8 to ~0.75 Ma). This change occurred in concert with an increase in aridity and most likely resulted from a decrease in summer monsoonal precipitation across southwestern North America due to global climate change during this time interval. Decreasing seasonality produced a relative decrease in C4 vegetation and a corresponding increase in C3 vegetation. A new equilibrium in the biota was established by 2.0 to 1.5 Ma, although the region probably experienced continued aridification that drove an increase in $\delta^{18}O$ in soil and surface waters from ~2.0 to 0.75 Ma. The decrease in seasonality of precipitation and increase in aridity affected soil processes in the basin and created a landscape dominated by calcic Aridisols. Increased aridity also produced a marked decrease in overall soil productivity. Data presented here are consistent with previous workers' interpretation that persistent ENSO conditions ended during late Pliocene time. Oxygen isotope ratios from the Fish Creek–Vallecito basin are incompatible with significant uplift of the Peninsular Ranges of southern California during late Pliocene and early Pleistocene time.

This paper presents a new data set that can be used to improve our understanding of how Plio-Pleistocene global climate change affected local climates in southern California. We conclude that the climate trends reported here resulted from progressive long-term global cooling, an end of persistent ENSO conditions in the Pacific Ocean, and shifts in the westerly jet stream due to growing ice masses over the northern hemisphere.

Supplementary materials related to this article can be found online at doi:10.1016/j.palaeo.2011.02.014.

Acknowledgments

We thank Kathryn Watts and Jim Palandri for laboratory assistance. Discussions with Bernie Housen and Mike Oskin. Thoughtful reviews by Jay Quade, Greg Retallack and an anonymous reviewer significantly improved this manuscript. Special thanks go out to George Jefferson for logistical support and Karen and Burnie Burnworth for their hospitality during repeated field seasons in Anza-Borrego Desert State Park. Funding for this study was provided by National Science Foundation grant EAR-0838119 to R.J. Dorsey and by the Geological Society of America Graduate Student Research Grant 8750-08 to T. Peryam. Stable isotope analysis costs were partly covered by National Science Foundation grant EAR-0844772 to I. Bindeman.

References

Abbot, P.L., Smith, T.E., 1989. Sonora, Mexico, source for the Eocene Poway Conglomerate of southern California. Geology 17 (4), 329–332.
Adams, D.K., Comrie, A.C., 1997. The North American Monsoon. Bulletin of the American Meteorological Society 78 (10), 2197–2213.
Amundson, R.G., Chadwick, O.A., Sowers, J.M., Doner, H.E., 1988. Relationship between climate and vegetation and the stable carbon isotope chemistry of soils in the eastern Mojave Desert, Nevada. Quaternary Research 29, 245–254.
Axelrod, D.I., 1973. In: di Castri, F., Mooney, H.A. (Eds.), History of the Mediterranean ecosystem in California. Ecological Studies, Analysis and Synthesis, 7. Springer-Verlag, pp. 225–277.
Axen, G.J., Fletcher, J.M., 1998. Late Miocene–Pleistocene extensional faulting, Northern Gulf of California, Mexico and Salton Trough, California. International Geology Review 40 (3), 217–244.
Blisniuk, P.M., Stern, L.A., 2005. Stable isotope paleoaltimetry: a critical review. American Journal of Science 305, 1033–1074.
Breecker, D.O., Sharp, Z.D., McFadden, L.D., 2009. Seasonal bias in the formation and stable isotopic composition of pedogenic carbonate in modern soils from central New Mexico, USA. Geological Society of America Bulletin 121 (3/4), 630–640.
Brogenski, C.B., 2001. Terrestrial evidence for Plio-Pleistocene climate change in oxygen and carbon isotopic values of Southern California horse teeth, M.S. Thesis, University of California, Davis, Davis, 91 pp.
Carey, D.L., 1976, Forms and processes in the pseudokarst topography of Arroyo Tapiado, Anza-Borrego Desert State Park, San Diego County, California, M.S. Thesis University of California, Los Angeles, Los Angeles, 126 pp.
Cassiliano, M.L., 1994. Biostratigraphy of Blancan and Irvingtonian mammals in the Fish Creek–Vallecito Creek section, Southern California, and a review of the Blancan-Irvingtonian boundary. Journal of Vertebrate Paleontology 19 (1), 169–186.
Caudill, M.R., Driese, S.G., Mora, C.J., 1996. Preservation of a paleo-Verisol and an estimate of Late Mississippian paleoprecipitation. Journal of Sedimentary Research 66 (1), 58–70.
Cayan, D.R., Dettinger, M.D., Diaz, H.F., Graham, N.E., 1998. Decadal variability of precipitation over Western North America. Journal of Climate 11 (12), 3148–3166.
Cerezo-Mota, R., Cavazos, T., Farfán, L.M., 2006. Numerical simulation of heavy precipitation in northern Baja California and southern California. Journal of Hydrometeorology 7, 137–148.
Cerling, T.E., 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. Earth and Planetary Science Letters 71 (2), 229–240.
Cerling, T.E., Quade, J., 1993. Stable Carbon and Oxygen Isotopes in Soil Carbonates, Climate Change in Continental Isotope Records: American Geophysical Union, pp. 217–231.
Cerling, T.E., Quade, J., Wang, Y., Bowman, J.R., 1989. Carbon isotopes in soils and paleosols as ecologic and paleoecologic indicators. Nature 341, 138–139.
Chamberlain, C.P., Poage, M.A., 2000. Reconstructing the paleotopography of mountain belts from the isotopic compotition of authigenic minerals. Geology 28 (2), 115–118.
Cosma, T.N., 2002a. Uplift of Peninsular Ranges affects terrestrial climate record of enhanced tropical moisture in late Pliocene, Anza-Borrego Desert, California. Geological Society of America Abstracts with Programs 34 (6), 45.
Cosma, T.N., 2002b. Late Tertiary climate variations inferred from ostracode data, Anza-Borrego Desert, Southern California, USA, M.S. Thesis, Kent State University, Kent, 108 pp.
Dekens, P.S., Ravelo, A.C., McCarthy, M.D., 2007. Warm upwelling regions in the Pliocene warm period. Paleoceanography 22.
Dorsey, R.J., Housen, B.A., Janecke, S.U., Fanning, M., Spears, A.L.F., 2011. Stratigraphic record of basin development within the San Andreas fault system: Late Cenozoic FIsh Creek–Vallecito basin, Southern California. Gelogical Society of America Bulletin. 123, 771–793.
Driese, S.G., Mora, C.I., 1993. Physico-chemical environment of pedogenic carbonate formation in Devonian vertic paleosols, central Appalachians, USA. Sedimentology 40, 199–216.

Dudal, R., Eswaran, H., 1988. Distribution, properties and classification of vertisols. In: Wilding, L.P., Puentes, R. (Eds.), Vertisols: their distribution, properties, classification and management. Texas A&M Publishing, College Station, pp. 1–22.
Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology 40, 503–537.
Fox, D.L., Koch, P.L., 2003. Tertiary history of C4 biomass in the Great Plains, USA. Geology 31 (9), 809–812.
Gensler, P.A., Jefferson, G.T., Roeder, M.A., 2006. In: Jefferson, G.T., Lindsay, L. (Eds.), The lower fossil vertebrates: fish, amphibians and reptiles. Fossil Treasures of the Anza-Borrego Desert. Sunbelt Publications, Inc., San Diego, pp. 139–146.
Graham, A., 1999. Late Cretaceous and Cenozoic history of North American Vegetation (North of Vegetation). Oxford University Press. 350 pp.
Haug, G.H., Tiedemann, R., Zahn, R., Ravelo, A.C., 2001. Role of Panama uplift on oceanic freshwater balance. Geology 29 (3), 207–210.
Haug, G.H., Granopolski, A., Sigman, D.M., Rosell-Mele, A., Swann, G.E.A., Tiedemann, R., Jaccard, S.L., Bollman, J., Maslin, M.A., Leng, M.J., Eglington, G., 2005. North Pacific seasonality and the glaciation of North America 2.7 million years ago. Nature 433, 821–825.
Haywood, A.M., Valdes, P.J., 2004. Modelling Pliocene warmth: contribution of atmosphere, oceans and cryosphere. Earth and Planetary Science Letters 218, 363–377.
Higgins, R.W., Yao, Y., Wang, X.L., 1997. Influence of the North American Monsoon system on the U.S. summer precipitation regime. Journal of Climate 10, 2600–2622.
Higgins, R.W., Chen, Y., Douglas, A.V., 1999. Interannual variability of the North American warm season precipitation regime. Journal of Climate 12, 653–680.
Howard, H.H., 1963. Fossil birds from the Anza-Borrego desert. Los Angeles County Museum Contributions in Science 73, 1–33.
Hsieh, J.C.C., Chadwick, O.A., Kelly, E.A., Savin, S.M., 1998. Oxygen isotopic composition of soil water: quantifying evaporation and transpiration. Geoderma 82, 269–293.
Intergovernmental Panel on Climate Change, 2007. Climate change, 2007: the scientific basis. Cambridge University Press, Cambridge. 996 pp.
Jolly, D.W., 2000. Fossil turtles and tortoises of Anza-Borrego Desert State Park, California, M.S. Thesis, Northern Arizona University, Flagstaff, 197 pp.
Kent-Corson, M.L., Sherman, L.S., Mulch, A., Chamberlain, C.P., 2006. Cenozoic topographic and climatic response to changing tectonic boundary conditions in Western North America. Earth and Planetary Science Letters 252, 453–466.
Kirby, S.M., et al., 2007. Pleistocene Brawley and Ocotillo formations: evidence for initial strike-slip deformation along the San Felipe and San Jacinto fault zones, Southern California. Journal of Geology 115, 43–62.
Kleinert, K., Strecker, M.R., 2001. Climate change in response to orographic barrier uplift: paleosol and stable isotopic evidence from the late Neogene Santa Maria basin, northwestern Argentina. Geological Society of America Bulletin 113 (6), 728–742.
Lewis, J.L., Day, S.M., Magistrale, H., Eakins, J., Vernon, F., 2000. Regional crustal thickness variations of the Peninsular Ranges, California. Geology 28, 303–306.
Lewis, J.L., Day, S.M., Magistrale, H., Castro, R.R., Astiz, L., Rebollar, C., Eakins, J., Vernon, F.L., Brune, J.N., 2001. Crustal thickness of the Peninsular Ranges and Gulf Extensional Province in the Californias. Journal of Geophysical Research 106, 13599–13611.
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20.
Lutz, A.T., Dorsey, R.J., Housen, B.A., Janecke, S.U., 2006. Stratigraphic record of Pleistocene faulting and basin evolution in the Borrego Badlands, San Jacinto fault zone, Southern California. Geological Society of America Bulletin 118 (11/12), 1377–1397.
Machette, M.N., 1985. Calcic soils of the southwestern United States. In: Weide, D.L. (Ed.), Soils and Quaternary geology of the southwestern United States. Geological Society of America, pp. 1–22.
Mack, G.H., James, W.C., 1994. Paleoclimate and the global distribution of paleosols. The Journal of Geology 102, 360–366.
Marrs, B., 2006. History of fossil collecting in the Anza-Borrego desert region. In: Jefferson, G.T., Lindsay, L. (Eds.), Fossil Treasures of the Anza-Borrego Desert. Sunbelt Publications, Inc., San Diego, pp. 1–23.
Minnich, R.A., Franco-Vizcaíno, E., Dezzani, R.J., 2000. The El Niño/Southern Oscillation and precipitation variability in Baja California, Mexico. Atmósfera 13, 1–20.
Mitchell, V.A., 1976. The regionalization of climate in the Western United States. Journal of Applied Meteorology 15 (9), 920–927.
Mitchell, D.L., Ivanova, D., Rabin, R., Brown, T.J., Redmond, K., 2002. Gulf of California sea surface temperatures and the North American Monsoon: mechanistic implications from observations. Journal of Climate 15, 2261–2281.
Mo, K.C., Higgins, R.W., 1998. Tropical influence on California precipitation. Journal of Climate 11, 412–430.
Molnar, P., Cane, M.A., 2002. El Niño's tropical climate and teleconnections as a blueprint for pre-Ice Age climates. Paleoceanography 17 (2).
Mueller, K., Kier, G., Rockwell, T., Jones, C.T., 2009. Quaternary rift flank uplift of the Peninsular Ranges in Baja and southern California by removal of mantle lithosphere. Tectonics 28.
Mundelsee, M., Raymo, M.E., 2005. Slow dynamics of the Northern Hemisphere glaciation. Paleoceanography 20.
Oskin, M., Stock, J., 2003. Pacific–North America plate motion and opening of the Upper Delfin basin, northern Gulf of California, Mexico. Geological Society of America Bulletin 115 (10), 1173–1190.
Quade, J., Cerling, T.E., Bowman, J.R., 1989. Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation tranxects in the southern Great Basin, USA. Geological Society of America Bulletin 101 (4), 464–475.
Quade, J., Cater, J.M., Ojha, T.P., Adam, J., Harrison, T.M., 1995. Late Miocene environmental change in Nepal and the northern Indian subcontinent: stable isotopic evidence from paleosols. Geological Society of America Bulletin 107 (12), 1381–1397.
Quade, J., Garzione, C., Eiler, J., 2007. Paleoelevation reconstruction using pedogenic carbonates. Reviews in Minerology and Geochemistry 66, 53–87.
Ravelo, A.C., Andreason, D.H., Lyle, M., Lyle, A.O., Wara, M.W., 2004. Regional climate shifts caused by gradual cooling in the Pliocene epoch. Nature 429, 263–267.
Raymo, M.E., 1994. The initiation of Northern Hemisphere glaciation. Annual Review of Earth and Planetary Sciences 22, 353–383.
Raymo, M.E., Grant, B., Horowitx, M., Rau, G.H., 1996. Mid-Pliocene warmth: stronger greenhouse and stronger conveyor. Marine Micropaleontology 27, 313–326.
Remeika, P., 2006. Ancestral woodlands of the Colorado River delta plain. In: Jefferson, G.T., Lindsay, L. (Eds.), Fossil Treasures of the Anza-Borrego Desert. Sunbelt Publications, Inc., San Diego, pp. 75–88.
Retallack, G.J., 1999. Postapocalyptic greenhouse paleoclimate revealed by earliest Triassic paleosols in the Sydney Basin, Australia. Geological Society of America Bulletin 111 (1), 52–70.
Retallack, G.J., 2005. Pedogenic carbonate proxies for amount and seasonality of precipitation in paleosols. Geology 33 (4), 333–336.
Retallack, G.J., Wynn, J.G., Fremd, T.J., 2004. Glacial-interglacial-sclae paleoclimatic change without large ice sheets in the Oligocene of central Oregon. Geology 32 (4), 297–300.
Sage, R.F., Wedin, D.A., Li, M., 1999. The biogeography of C4 photosynthesis: patterns and controlling factors. In: Sage, R.F., Monson, R.K. (Eds.), C4 Plant Biology. Academic Press, San Diego, pp. 313–376.
Schoenherr, A.A., Burk, J.H., 2007. Colorado Desert vegetation. In: Barbour, M.G., Keeler-Wolf, T., Schoenherr, A.A. (Eds.), Terrestrial Vegetation of California. University of California Press, Berkeley, pp. 657–682.
Schrag, D.P., Hampt, G., Murray, D.W., 1996. Pore fluid constraints on the temperature and oxygen isotopic composition of the glacial ocean. Science 272, 1930–1932.
Sheldon, N.D., Retallack, G.J., 2001. Equation for compaction of paleosols due to burial. Geology 29 (3), 247–250.
Sheldon, N.D., Tabor, N.J., 2009. Quantitative paleoenvironmental and paleoclimatic reconstruction using paleosols. Earth-Science Reveiews 95, 1–52.
Smith, G.I., 1984. Paleohydraulic regimes in the southwestern Great Basin, 0–3.2 my ago, compared with other long records of "global" climate. Quaternary Research 22, 1–17.
Smith, G.A., Wang, Y., Cerling, T.E., 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 21, 691–694.
Soil Survey Staff, 1999. Soil Taxonomy: United States Department of Agriculture Handbook, 436.
Spaulding, W.G., 1991. Pluvial climatic episodes in North America and North Africa: types and correlations with global climate. Palaeogeography, Palaeoclimatology, Palaeoecology 84, 217–227.
Spero, H.L., Brogenski, C.B., Jefferson, G.T., 2003. Initiation of modern Pacific atmospheric circulation at the Plio-Pleistocene boundary recorded in horse teeth enamel geochemistry. Geological Society of America Abstracts with Programs 35 (6), 586.
Steely, A.N., Janecke, S.U., Dorsey, R.J., Axen, G.J., 2009. Early Pleistocene initiation of the San Felipe fault zone, NW Salton Trough, during reorganization of the San Andreas fault system. Geological Society of America Bulletin 121, 663–687.
Stevenson, B.A., Kelly, E.F., McDonald, E.V., Busacca, A.J., 2005. The stable carbon isotope composition of soil organic carbon and pedogenic carbonates along a bioclimatic gradient in the Palouse region, Washington State, USA. Geoderma 124, 37–47.
Sussman, S., Lindsay, L., Spero, H., 2006. Paleoclimates and environmental change in the Anza-Borrego Desert region. In: Jefferson, G.T., Lindsay, L. (Eds.), Fossil Treasures of the Anza-Borrego Desert. Sunbelt Publications, Inc., San Diego, pp. 339–352.
Tipple, B.J., Meyers, S.R., Pagani, M., 2010. Carbon isotope ratio of Cenozoic CO_2, a comparative evaluation of available geochemical proxies. Paleoceanagraphy 25, 11.
Van Devender, T.R., 1990. Late Quaternary vegetation and climate of the Sonoran desert, United States and Mexico. In: Betancourt, J.L., Van Devender, T.R., Martin, T.S. (Eds.), Packrat Middens: The Last 40,000 Years of Biotic Change. University of Arizona Press, Tucson, pp. 134–165.
Vaughan, T.W., 1904. A California Tertiary coral reef and its bearing on American recent coral reefs. Science 19.
Wara, M.W., Ravelo, A.C., Delaney, M.L., 2005. Permanent El Niño-like conditions during the Pliocene warm period. Science 309, 758–761.
White, J.A., Wagner, H., Jefferson, G.T., 2006. The small fossil mammals: rodents, rabbits and their relatives. In: Jefferson, G.T., Lindsay, L. (Eds.), Fossil Treasures of the Anza-Borrego Desert. Sunbelt Publications, Inc., San Diego, pp. 235–251.
Wieder, M., Yaalon, D.H., 1974. Effect of matrix composition on carbonate nodule crystallization. Geoderma 11, 95–121.
Williams, A.E., Rodoni, D.P., 1997. Regional isotope effects and application to hydrologic investigations in southwestern California. Water Resources Research 33 (7), 1721–1729.
Woodhouse, C.A., 1997. Winter climate and atmospheric circulatioon in the Sonoran Desert region, USA. Journal of Climatology 17, 859–873.
Yang, Y., Forsyth, D.W., 2006. Rayleigh wave phase velocities, small-scale convection, and azimuthal anisotropy beneath Southern California. Journal of Geophysical Research 111, 20.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rythms, and abberations in global climate 65 Ma to the present. Science 292, 386–392.