LATE QUATERNARY ENVIRONMENTS OF THE NORTHERN DESERTS AND CENTRAL TRANSVOLCANIC BELT OF MEXICO[1]

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Abstract

The detailed nature of climatic change over the late Quaternary remains poorly understood for northern and central Mexico. A scarcity of records in the former and great complexity in the latter have hindered a thorough reconstruction of changing environments. Previously published research by Metcalfe et al. highlighted questions relating to conditions at the last glacial maximum (LGM), the nature of the transition from glacial to interglacial conditions, and change over the Holocene, including the role of phenomena such as El Niño–Southern Oscillation (ENSO). Here, data from the Sonoran Desert, the Chihuahuan Desert, and the Trans-Mexican Volcanic Belt (TMVB) (and adjacent oceans) are reviewed. In the desert regions, the mid-Pleistocene may have been drier than the late Pleistocene, which was significantly cooler than present and saw more winter precipitation derived from midlatitude frontal systems. There was a significant expansion southward of woodland taxa, although many fossil vegetation assemblages apparently have no modern analogues. Extensive paleolakes existed in the modern desert. Conditions wetter than present persisted into the Holocene, but the modern summer rainfall regime may not have become established until after 9000 uncalibrated radiocarbon-dated years before present (^{14}C yr. BP). Fully modern conditions started about 4000 ^{14}C yr. BP. In the TMVB, sparse lake sediment records indicate that the mid-Pleistocene may have been wetter than the late Pleistocene. Further data are still required to confirm whether the proposed pattern of a wet west and a dry east around the LGM holds true. Most lake sediment records show major anthropogenic influence from the mid-Holocene on, although there is evidence for increasing climatic variability in the late Holocene. New deep sea core records indicate the glacial meltwater was re-routed into the Gulf of Mexico after the Younger Dryas cool event, helping to explain the delayed onset of the modern summer rainfall pattern in relation to general warming. High-resolution records are still confined to deep sea cores and tree rings, but highlight the region's vulnerability to climatic change.

Keywords: Chihuahua, climate change, late Quaternary, Mexico, Sonora, Trans-Mexican Volcanic Belt.

Resumen

La naturaleza detallada del cambio climático durante el Cuaternario tardío en el norte y centro de México es aún poco entendida. La escasez de registros en el primero y la complejidad del segundo, han dificultado una reconstrucción detallada de ambientes cambiantes. La investigación previamente publicada por Metcalfe et al. destaca preguntas relacionadas a las condiciones durante la máxima de último glacial (LGM), la naturaleza de la transición de glacial a las condiciones interglaciales, y de cambio durante el Holoceno, incluyendo el papel de fenómenos tales como El Niño–oscilación meridional (ENSO). Aquí se revisan los datos del desierto de Sonora, el desierto de Chihuahua y el cinturón volcánico trans-mexicano (TMVB) (y los océanos adyacentes). En las regiones desérticas, el Pleistoceno medio pudo haber sido más seco que el Pleistoceno tardío, que fue significativamente más frío que el presente y tuvo más precipitación invernal derivada de sistemas frontales de latitudes medias. Hubo una expansión significativa de taxones leñosos hacia el sur, aunque muchos grupos fósiles de vegetación al parecer no tienen ningún análogo moderno. Paleolagos extensos existieron en el desierto moderno. Condiciones más húmedas que las actuales persistieron en el Holoceno, pero el régimen de lluvias de verano moderno pudo no haberse establecido hasta después 9000 años de radiocarbono no calibrados antes del presente (^{14}C yr. BP). Condiciones completamente modernas comenzaron cerca de 4000 ^{14}C yr. BP. En el TMVB, escasos registros de sedimentos lacustres indican que el Pleistoceno medio pudo haber sido más húmedo que el Pleistoceno tardío. Todavía se requieren datos adicionales para confirmar si el propuesto patrón de un oeste húmedo y un este seco alrededor del LGM es verdadero. La mayoría de registros lacustres demuestran una importante influencia antropogénica desde mediados del Holoceno hacia adelante, aunque hay evidencia de un aumento en la variabilidad climática en el Holoceno tardío. Los registros profundos del fondo del mar indican que el aguanieve glacial fue reencaminada hacia el golfo de México después del evento del enfriamiento del joven Dryas, lo que ayuda a explicar el inicio retrasado del patrón moderno de la precipitación de verano en relación al calentamiento general. Registros de alta resolución todavía se confinan a muestras del fondo del mar y a anillos de árboles, pero destacan la vulnerabilidad de la región a los cambios climáticos.

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The late Quaternary saw the transition from a glacial climate (with the global glacial maximum at 18,000 uncalibrated radiocarbon-dated years before present (^{14}C yr. BP)) into the modern interglacial climate at about 10,000 ^{14}C yr. BP. Although the broad patterns of climatic change over this period in tropical and sub-tropical areas have been identified (e.g., Gasse, 2000), the detailed nature of change remains poorly understood. This is particularly true for northern and central Mexico. Records from northern Mexico, especially terrestrial records, are scarce, and in central Mexico the complexity of the environment has hindered making climatic reconstructions. In practice, most records are also confined to the past 70,000 years or so (the mid-Pleistocene ca. 70,000–45,000 before present (BP), equivalent to marine isotope stage 3).

Global climatic change during the Pleistocene and Holocene brought about major changes in precipitation regimes (amount and seasonality), as well as changes in temperature and sea level. In general, the glacial world was drier than the interglacial world, but there are regional variations to this pattern. The area to the southwest of the Laurentide ice sheet, including present day northern Mexico, was one area of increased moisture availability around the LGM (COHMAP Members, 1988; Thompson et al., 1993). In tropical and subtropical areas, moisture availability is a key aspect of climatic change, bringing about major shifts in drainage systems and vegetation distributions.

The nature of climatic and environmental change can be reconstructed using a range of sources, or proxies. Most of these proxies provide records of relatively low temporal resolution (e.g., decadal, centennial) depending on the rate at which material accumulates. Key sources of low-resolution data are lake cores, ocean cores, glacial records, packrat middens, and paleosols. Some records, however, have annual (or even seasonal) resolution; these include some ocean cores and lake cores, ice cores, tree rings, and historical and instrumental records. This paper reviews climate records from central and northern Mexico and the adjacent oceans based on a wide range of proxies. The focus here is on records that have been published since the reviews of Metcalfe et al. (2000) and Fritz et al. (2001). The chosen study area includes the modern Sonoran and Chihuahuan deserts and the highlands of the Trans-Mexican Volcanic Belt (TMVB) (Figure 1).

The Climate of Mexico

The modern climate of Mexico is dominated by seasonal shifts in the position of the Inter-Tropical Convergence Zone (ITCZ), the position and intensity of subtropical high-pressure cells (e.g., the Bermuda-Azores High), and the frequency and extent of midlatitude westerly depressions. In winter, with the ITCZ in a southerly position (Fig. 2a), most of Mexico is dominated by high pressure, resulting in dry conditions. Cyclonic systems, originating in the Pacific Ocean, affect northwestern and central Mexico and bring frontal rainfall. A very small area of northwest Mexico (primarily the west coast of Baja California) receives most of its precipitation in winter. On the east side of Mexico, some precipitation is brought by *nortes*, cold winds originating over North America that pick up moisture over the Gulf of Mexico (Mosiño Aleman & Garcia, 1974). In summer, the ITCZ moves north, and moist, easterly flow is established over the country (Fig. 2b). This has been identified as a monsoonal-type circulation. The period June to September is the main wet season over most of Mexico. The principal source of moisture is the Gulf of Mexico, with flows extending up into the Great Plains of the United States and Canada. On the west side of Mexico, a low-level flow, called the Mexican Monsoon, becomes established, drawing moisture northward along the Pacific margin, through the Gulf of California (or Sea of Cortez), and into the southwestern United States (Douglas et al., 1993; Higgins et al., 1998). Convective storms and tropical storms (originating over both the Pacific Ocean and Gulf of Mexico/Atlantic Ocean) make a significant contribution to summer precipitation (e.g., Englehart & Douglas, 2001).

The position and strength of the key features influencing pressure distributions and, hence, precipitation are known to be affected by climatic phenomena such as El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO). Although the effects of ENSO are complex in this region, in broad terms El Niño years see increased winter precipitation in northwest Mexico and drier summers overall (Magaña et al., 2003), while La Niña years result in more summer precipitation.

Across the whole of Mexico, both precipitation and temperature are strongly affected by altitude and aspect (Fig. 3a). The highlands of the TMVB, which cross Mexico at about 19°N (Fig. 1), have a remarkably temperate climate because much of the land lies above 2000 m, with the highest peaks reaching more than 5000 m and supporting permanent ice cover. Pine and oak forests are the dominant natural vegetation over most of the TMVB. In northern Mexico, the highlands of the Sierra Madre Oriental and Occidental are similar to the TMVB (Fig. 3b). The plateau area between these ranges (the Mesa Central)

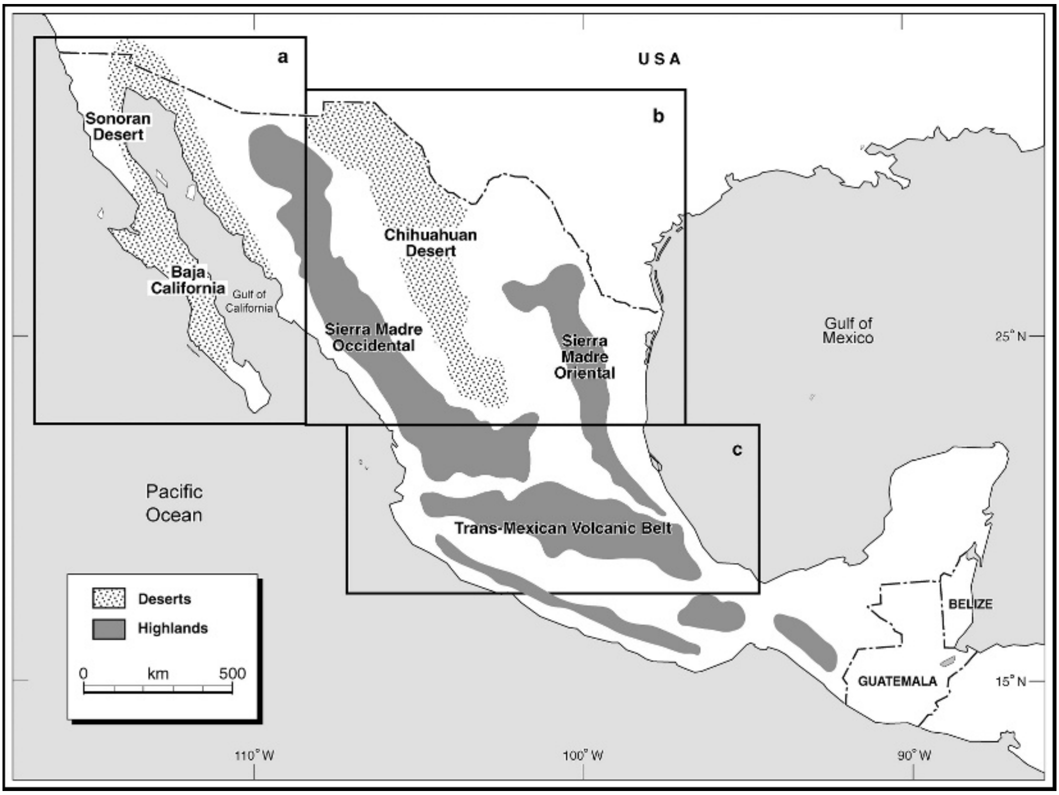

Figure 1. Main topographical features of Mexico showing the locations of the study areas. —a. Baja/Sonora. —b. Chihuahua. —c. Trans-Mexican Volcanic Belt.

declines in elevation northward toward the modern Mexico–U.S.A. border. Lower altitudes, the increasing predominance of subtropical high pressure, and distance from moisture sources give rise to the Chihuahuan Desert. Annual precipitation in the border area is about 200 mm, and there are areas of active dunes. The vegetation of the modern Chihuahuan lowlands is dominated by creosote bush (*Larrea tridentata* (Sessé & Moçiño ex DC.) Coville), with a range of other shrubs; yuccas, especially soaptree yucca (*Yucca elata* (Engelm.) Engelm.); agaves; cacti; and grasses. In northwestern Mexico, dry conditions are exacerbated by the occurrence off-shore of the cold California current. Areas of Baja California and Sonora are the driest in Mexico, with less than 100 mm of rain annually (Fig. 3a). This broad area lies within the Sonoran Desert. Here a summer rainfall maximum is the norm, except for parts of Baja California and coastal Sonora that are exposed to winter frontal systems (see above). Although creosote bush occurs in the Mexican part of the Sonoran Desert, it is not as abundant as it is farther north. Lowland vegetation includes many forms of cacti, yuccas, agaves, and forms of ocotillo, including the boojum tree (*Fouquieria columnaris* (Kellogg) Kellogg ex Curran). Rzedowski (1973) has highlighted the diversity of vegetation in Mexican dryland areas and the distinct differences between the Chihuahuan and Sonoran floras.

BAJA/SONORA

Today, this area of northwest Mexico (Fig. 1) is extremely dry (see above), and the range of terrestrial sites that have preserved paleoclimatic records is very limited. Sources of paleoclimatic data include tree rings, packrat middens, lake sediments, and deep sea cores (Fig. 4). Although tree ring records from this area extend back into the 15th century, there are no other proxy records for comparison, and no attempt has been made to relate the tree ring records to archival records. As a result, the tree ring data will not be discussed here.

Most of the paleoclimate data for this region comes from packrat (*Neotoma* Say & Ord) middens. Packrat middens preserve plant macrofossil remains, which allow reconstruction of local vegetation to species level. They may also contain pollen, which allows

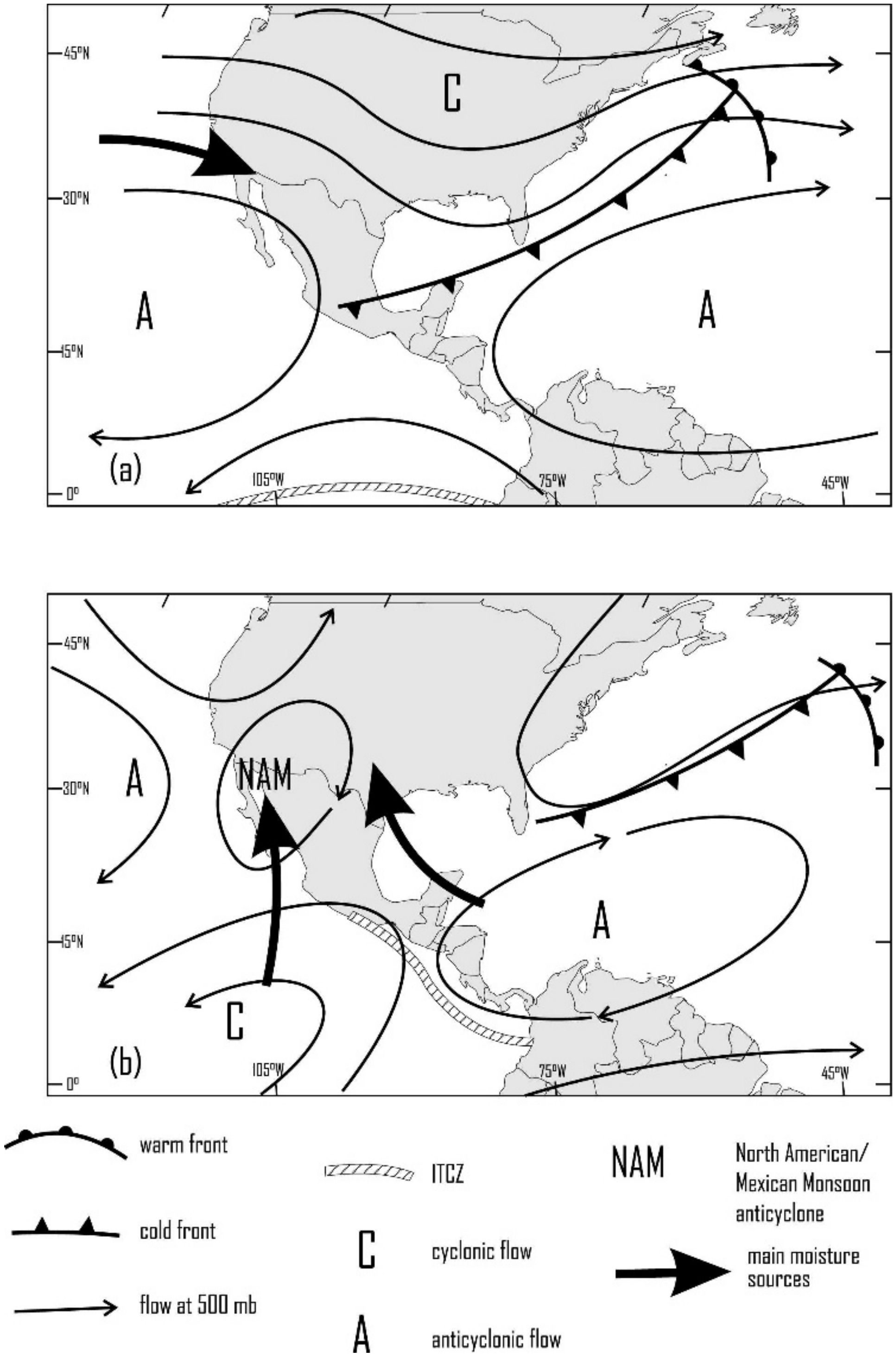

Figure 2. Main features of the atmospheric circulation across Mexico. —a. In winter. —b. In summer. ITCZ = Intertropical Convergence Zone. Redrawn after Metcalfe et al. (2000).

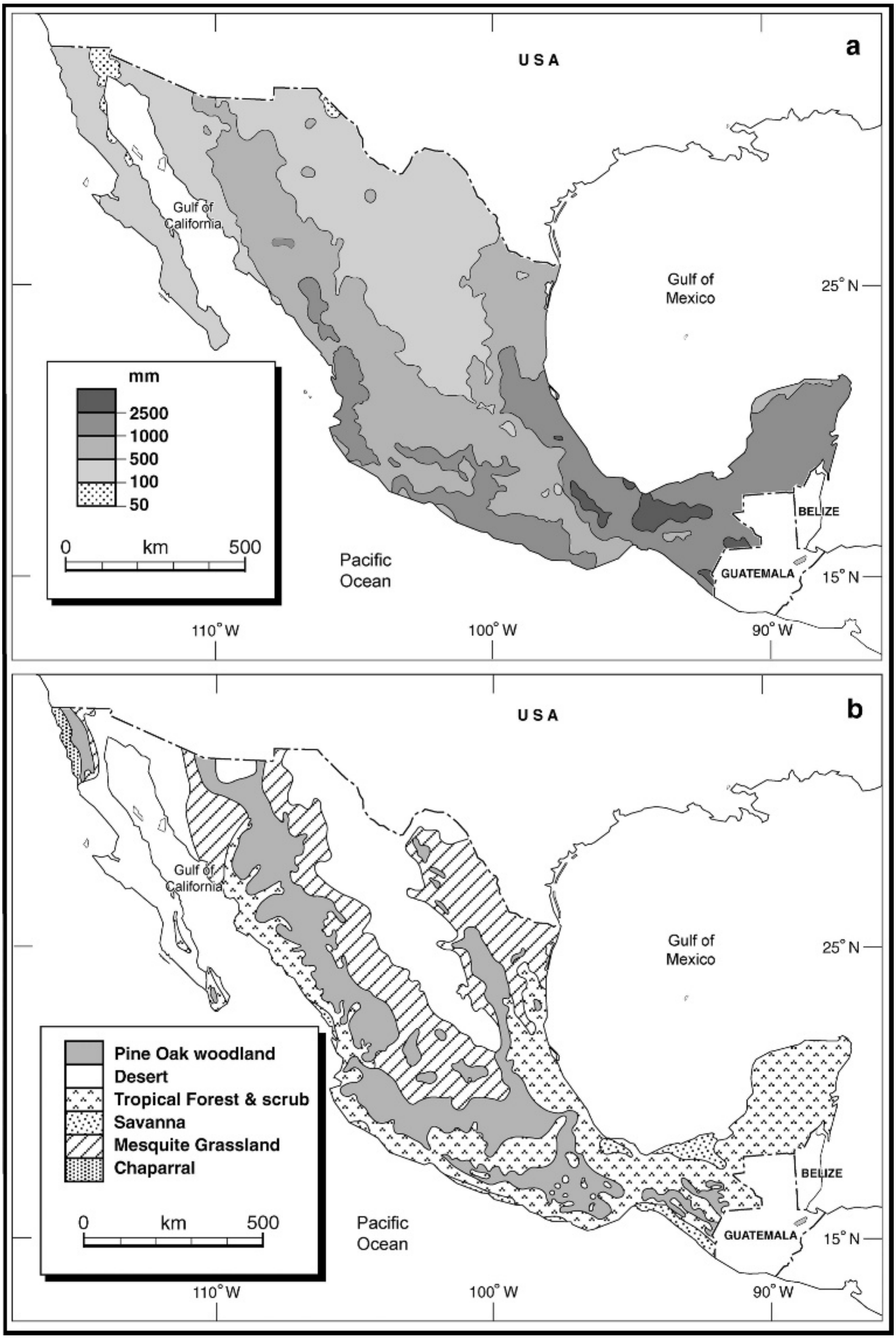

Figure 3. —a. Total annual precipitation, —b. Major vegetation types across Mexico. (a, based on data for 1941–2002 from the Servicio Meteorológico Nacional, Mexico; b, based on data from the Instituto Nacional de Estadística, Geografia e Informatica, and Rzedowski (1994)).

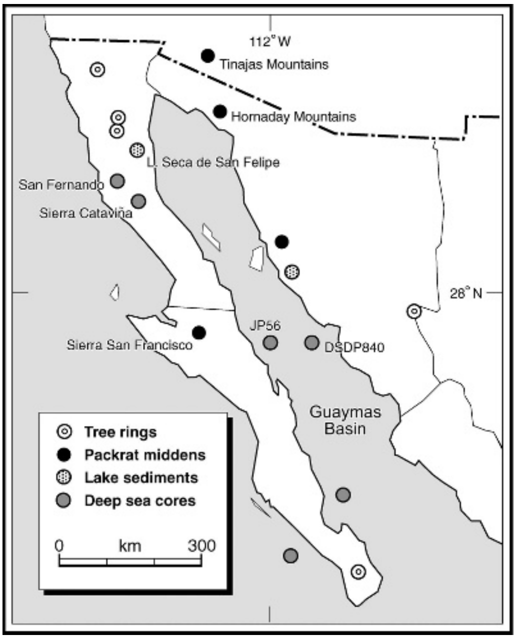

Figure 4. Sources of paleoclimatic data for the Baja/Sonora region. Sites referred to in the text are named.

reconstruction of both regional and local vegetation (Anderson & Van Devender, 1995), but only to generic or family level. Species-level identification of paleovegetation is an asset to reconstructing climate, because it can be used to identify the season of precipitation; this is a key concern in both Baja/Sonora and Chihuahua. The longest midden records from Baja California (Sierra Cataviña and San Fernando) extend back ca. 30,000 years (Van Devender, 1990a; Peñalba & Van Devender, 1997; Van Devender, 1997), while a record from the Tinajas Mountains (just over the border in Arizona) reaches back to 43,000 BP (Van Devender, 1990a). Although the amount of data is limited, it appears that in this area the mid-Pleistocene may have been drier than the late Pleistocene (Van Devender, 1990a). The mid-Pleistocene middens from Tinajas include Joshua tree (*Yucca brevifolia* Engelmann), a Mojave desert species that is not found in the late Pleistocene middens. In contrast, single leaf pinyon (*Pinus monophylla* Torrey & Fremont), although present, is more common in the late Pleistocene. The late Pleistocene (full glacial, equivalent to marine isotope stage 2) seems to have been significantly cooler than present (by 5° to 6°C), with more winter precipitation. Pinyon (e.g., Parry pinyon (*Pinus quadrifolia* Parlatore ex Sibworth)), juniper (e.g., western juniper (*Juniperus occidentalis* Hooker)), and chaparral species were present more than 400 km south of their present day distributions in southern California and northern Baja California. A record from the Sierra San Francisco (Rhode, 2002), 300 km south of Sierra Cataviña (Fig. 4), which is today vegetated with scrub and succulents, confirms the southward expansion of juniper and chaparral vegetation even at relatively low elevations (< 800 m). Based on the modern distribution of California juniper (*Juniperus californica* Carrière) and other taxa, this area of central Baja California may have experienced a mild, Mediterranean climate in the late Pleistocene and early Holocene, with at least twice as much winter precipitation as it receives today.

It is interesting to note that many of the late Pleistocene vegetation communities recorded in the middens have no complete modern analogues. This may indicate that although the late Pleistocene climate here was similar to that of present day southern California, there were some differences. Woodland plants apparently persisted in this area into the early Holocene (at least at elevations above 250 m). Cooler summers and greater winter precipitation seem to have continued. Middens from the Hornoday Mountains in northwest Sonora, close to the Gran Desierto, however, do not show the woodland plants found in other Sonoran Desert sites at this time. From about 9000 ^{14}C yr. BP, the winter rainfall regime seems to have collapsed and the modern, summer rainfall–dominated climate regime became established. Pinyon-juniper-oak woodland, with chaparral species, were replaced by juniper-oak chaparral and, finally, by Sonoran desert scrub (Van Devender, 1997).

The middle Holocene was warmer and generally wetter than present (more summer rain). Middens from Cataviña, however, show that woodland and chaparral elements had died out and been replaced by mesquite (*Prosopis* sp.) and then cactus (Van Devender, 1997). An increasing abundance of C$_4$ grasses is often taken as being indicative of more summer rainfall, although their interpretation in the fossil record has been disputed (Van Devender et al., 1990; Holmgren et al., 2003). McAuliffe and Van Devender (1998) report that frost-intolerant taxa were present in the northern Sonoran Desert and suggest that temperatures in the early to mid-Holocene were 2°C warmer than present. They also point out that more frequent tropical cyclones may have contributed to increased overall precipitation levels. These mid-Holocene conditions are consistent with insolation changes driven by Milankovitch forcing. The present day vegetation of Sonoran desert scrub and cactus seems to have been established about 4000 BP.

Lake sediment records from Baja/Sonora are extremely scarce. There are paleolake basins, but poor microfossil preservation and difficulties with obtaining a reliable chronology have severely limited the usefulness of those that have been studied. The best dated record comes from the Laguna Seca San Felipe in Baja California (Ortega et al., 1999; Lozano García et al., 2002), with a core covering the period from about 70,000 to 4000 ^{14}C yr. BP. The sequence indicates a relatively dry mid-Pleistocene followed by a wetter late Pleistocene. The pollen record indicates the presence of open pine and juniper woodland in the mid-Pleistocene, with an expansion of juniper woodlands in the late Pleistocene. Strong summer cooling and increased winter precipitation are proposed as the most likely explanation for the observed changes in vegetation. Planktonic, saline water diatoms are present for the period from 34,000 to 28,000 BP, and lacustrine conditions seem to have persisted until about 12,000 BP. There is some suggestion that the Younger Dryas (11,000 to 10,000 ^{14}C yr. BP) was dry but that conditions wetter than present marked the early Holocene through to 7000 BP. No pollen record was preserved in these sediments. Aeolian sediments mark drying in the mid-Holocene, and about the last 4000 years of the record seem to have been lost. Although the record from Laguna Seca has a number of problems, it does seem to be remarkably consistent with that derived from the much more abundant midden data.

Unlike the terrestrial environment, conditions in the Gulf of California (Fig. 1) are conducive to well-preserved and high-resolution paleoclimate records. A large number of deep sea cores have been retrieved from this area, particularly from the Guaymas Basin. High productivity and anoxic conditions at depth have resulted in the deposition of laminated sediments giving the potential for seasonal resolution (Pike & Kemp, 1997). There are periods of non-laminated (massive) sedimentation, such as during the full glacial and Younger Dryas periods. Despite these promising conditions, the interpretation of records from the Gulf of California is far from straightforward. Sancetta (1995) reported results from core JP56 (western Guaymas Basin, Fig. 4) that suggested weak westerly winds in the late glacial and Younger Dryas periods, but more El Niño–like conditions and an increase in westerly winds into the early Holocene. This pattern of change is quite inconsistent with that derived from terrestrial records (in Baja/Sonora and the nearby southwest U.S.A.) and with modelling results. By the mid-Holocene, however, the record from JP56 is consistent with terrestrial records as modern conditions are indicated.

A more recent record (Barron et al., 2004) from the eastern Guaymas Basin (core DSDP 840) has highlighted the difficulties of matching marine and terrestrial records in the late Pleistocene. The authors use percent weight $CaCO_3$ as an indicator of tropical ocean influence. High percentages in the late glacial and Younger Dryas periods seem to indicate warm conditions, and the Younger Dryas sediments also have a higher number of tropical diatom species. The straightforward interpretation of the Younger Dryas sediments is that they reflect the persistence of tropical ocean influence (today a summer and autumn phenomenon). However, the authors note that this apparent warmth is inconsistent with both the midden data (see above) and the results from deep sea cores taken farther north in the Santa Barbara Basin and elsewhere off the California coast. The DSDP 840 core shows an abrupt change in the early Holocene, with an increase in productivity. Cooler and more saline conditions in the early to mid-Holocene are explained as being due to intensified northwest winds; however, this is difficult to reconcile with the terrestrial records. A spike in productivity at 8200 BP (ca. 7400 ^{14}C yr. BP) is attributed to a cold event in the North Atlantic brought about by the catastrophic drainage of Lake Agassiz. This cold event (also seen in the Greenland GISP2 ice core) apparently resulted in stronger westerlies and more upwelling, driving an increase in productivity. Around approximately 6200 BP (5400 ^{14}C yr. BP), the core record shows the onset of modern ENSO conditions, which have occurred with increasing frequency over the last 3000 years. Unfortunately, there are no long terrestrial ENSO records for comparison, but the onset of the modern ENSO regime about 5000 BP has been reported elsewhere (Rodbell et al., 1999; Tudhope et al., 2001; Moy et al., 2002).

Over shorter timescales, ENSO records are preserved in tree rings (Stahle & Cleaveland, 1993). In this area, tree growth appears to be responsive to increased winter precipitation during El Niño events (although summers are dry). The PDO shows ENSO-type features over longer time scales, with warm (positive) phases being El Niño–like (eastern Pacific warm) and cool (negative) phases being La Niña–like (eastern Pacific cool) (Higgins et al., 2003). Evidence for low frequency variability (40-year and 80-year cycles) consistent with the PDO has been found by combining tree ring and reconstructed streamflow data from the Gulf of California watershed (Brito Castillo et al., 2003).

Chihuahua

This area is taken to include the Mexican part of the Chihuahuan Desert, covering the modern states of Chihuahua, Coahuila, Durango, northern Zacatecas, and parts of Nuevo Leon and Tamaulipas (Fig. 1). As

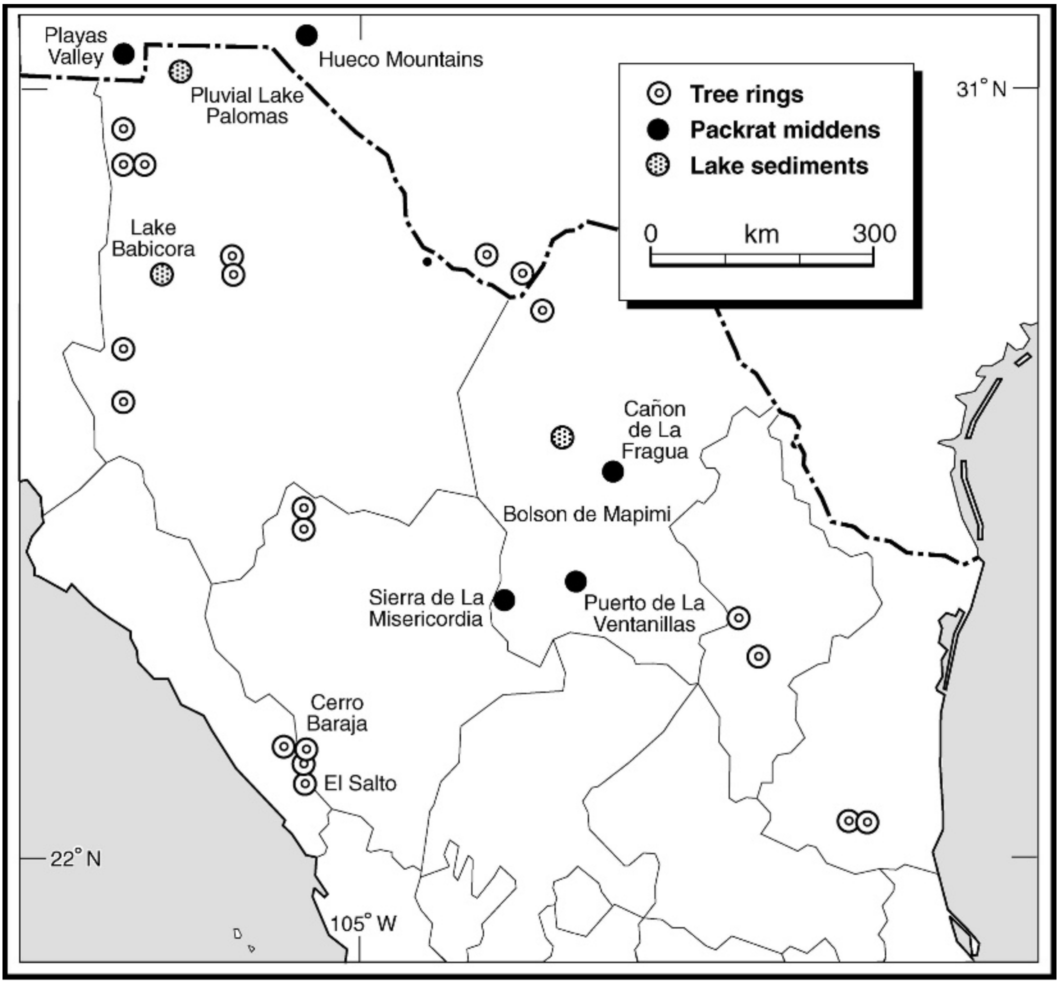

Figure 5. Sources of paleoclimatic data for the Chihuahua region. Sites referred to in the text are named.

described above, summer rainfall predominates here, with strong altitudinal and latitudinal gradients. As in Baja/Sonora, key paleoclimatic data for the Chihuahuan area (Fig. 5) have come from packrat middens, although there are few records for the Mexican part of the Chihuahuan Desert compared with the part within the U.S.A. Middens from the Hueco Mountains (west Texas, Fig. 5) provide a record covering about 42,000 years (Van Devender, 1990b). These record the presence of woodlands with sandpaper bush and big sagebrush (*Artemisia tridentata* Nuttall type) in the mid-Pleistocene. Sandpaper bush and big sagebrush are generally considered to be Great Basin plants; their presence indicates that their range extended southward in this period. They are only rarely present in late Pleistocene and Holocene middens. There are three records from the Bolson de Mapimi (Coahuila) that cover about the last 13,000 years (Van Devender & Burgess, 1985). These show that in the late glacial period, the vegetation of the area was a woodland of juniper and papershell pinyon (*Pinus remota* (Little) L. H. Bailey & Hawksworth), but that these were replaced by Chihuahuan desert scrub and succulents between 12,000 and 9000 ^{14}C yr. BP. This change from woodland to scrubland vegetation occurred earlier here than in Baja/Sonora.

By including midden data from the whole of the Chihuahuan Desert (e.g., Betancourt et al., 2001; Holmgren et al., 2003), a longer and more complete record of climatic change can be obtained. In the Chihuahuan Desert, it appears that the mid-Pleistocene was drier than the late Pleistocene only at the lowest elevations (cf. Baja/Sonora). The late Pleistocene was marked by cooler summers and mild, wet winters, but it seems that there was still some summer rainfall (shown by C_4 grasses and summer annuals).

These wetter conditions resulted in an expansion of pinyon-juniper woodland, including papershell pinyon and Colorado pinyon (*P. edulis* Engelmann), as far south as 26°N. As in Baja/Sonora, there are no modern analogues for some of these late Pleistocene communities, particularly those in modern New Mexico.

In the early Holocene, winters still seem to have been wetter than present, although the limit of winter rainfall was apparently tracking northward by 9000 BP. The modern climatic regime was established between 9000 and 8000 BP as desert shrubs replaced the woodland taxa (except at high elevations). It has been noted that some vegetation types responded very rapidly to increasing summer temperatures and precipitation. Conditions wetter than present apparently persisted through the early Holocene, driven by summer (monsoonal) rain, although midden records are quite scarce. Holmgren et al. (2003) explain the lack of mid-Holocene (8000 to 4000 BP) middens in the Playas Valley (southwestern New Mexico, in the U.S.A.–Mexico border area) as being due to persistent winter drought that led to a decline in woody perennials. As in Baja/Sonora, modern conditions seem to have set in about 4000 BP with the arrival of desert scrub species including creosote bush.

As in the Sonoran Desert region, lake sediment records in Chihuahua are few and microfossil preservation is often poor. There does, however, seem to be much more potential for records from the Chihuahuan area because it is the southward extension of the Basin and Range province and because there are extensive paleolake basins. The earliest work in the area was a pollen record from the Bolson de Mapimi published by Meyer (1973). This apparently showed little change in vegetation (and hence climate), although the midden data from the same area contradict this. More recent records have come from farther north and confirm that the area has experienced significant climatic change over the late Quaternary. The Babicora Basin, at 2200 m in the foothills of the Sierra Madre Occidental (Fig. 5), has been the focus of most work (Metcalfe et al., 2002; Ortega Ramirez et al., 1998; Palacios-Fest et al., 2002). Cores from the basin floor and sections from the basin margins have provided a record covering about the last 65,000 years. Diatom, pollen, and geochemical data show that an extensive lake occupied the Babicora Basin throughout the mid- to late Pleistocene and into the early Holocene. The diatom record shows strong fluctuations in conditions in the mid-Pleistocene (with a period of enhanced evaporation) that are consistent with the midden data. Cool conditions around the LGM are indicated by the presence of forests of fir (*Picea* A. Dietrich) and pine. It is clear from the Babicora record and from lake level records elsewhere in the Great Basin that the dry conditions of the late Holocene are very unusual. The increased moisture availability across this area in the middle and late Pleistocene is thought to be the result of increased winter precipitation (Bradbury et al., 2000). The Holocene record from Babicora is rather patchy, particularly from the cores. A change in dominant diatom taxa in the early Holocene is thought to indicate a shift to summer precipitation (Metcalfe et al., 2002). A permanent lake seems to have persisted into the mid-Holocene, but with strong variability in water level (Ortega Ramirez et al., 1998). Dry conditions are indicated around 5000 BP. An analysis of Mg/Ca ratios in ostracods (Palacios-Fest et al., 2002) from the late Holocene (after 4000 BP) has been interpreted as indicating colder winters with more effective moisture, possibly more winter precipitation. This would be consistent with the southward shift of the ITCZ from the mid-Holocene (see below), making summer precipitation less dominant.

A more detailed Holocene record has been published for lakes El Fresnal and Santa Maria a little farther north of Babicora (Castiglia & Fawcett, 2001, 2006). These basins were part of Pleistocene paleolake Palomas (Fig. 5), but Castiglia and Fawcett (2001, 2006) report the occurrence of large lakes in the Holocene, including the Little Ice Age. The largest Holocene lake seems to have been present around 8000 BP and covered more than 5600 km^2. The mid-Holocene showed high variability, with a reasonably extensive lake in 6000 and 4000 BP, but with dry conditions at 5000 BP. The authors suggest that millennial-scale high stands may be linked to Bond cycles in the North Atlantic and that the Holocene high stands may reflect increased winter precipitation associated with increasing El Niño events (see above).

Consideration of all the published terrestrial long-term climate records from northern Mexico and adjacent areas yields a very consistent picture of change since the mid-Pleistocene. The Pleistocene was cooler than present (up to 5° to 6°C around the LGM) and generally wetter, with the mid-Pleistocene drier than the late Pleistocene. Pinyon and juniper woodland extended over substantial areas of what are now the Chihuahuan and Sonoran deserts, and chaparral vegetation extended into southern Baja California. Some of the vegetation communites recorded in packrat middens have no modern analogues. Extensive lakes and wetlands occupied basins in present day Chihuahua and Coahuila. The data seem to support previous explanations that wetter conditions were driven by increased winter precipitation originating over the Pacific Ocean and driven southward by the mass of the Laurentide ice

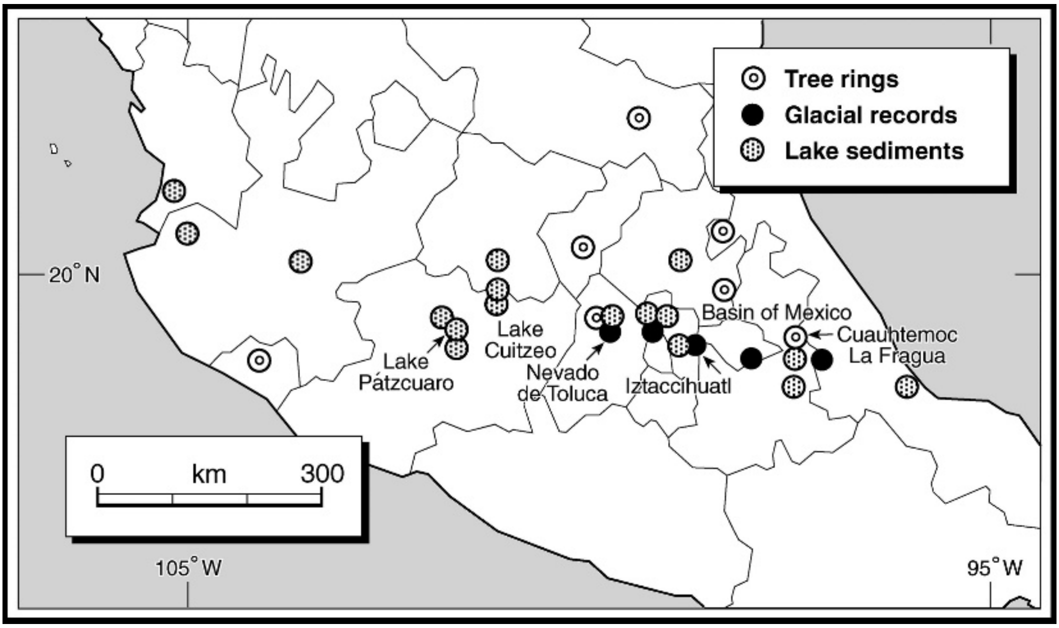

Figure 6. Sources of paleoclimatic data for the Trans-Mexican Volcanic Belt. Sites referred to in the text are named.

sheet (COHMAP Members, 1988; Thompson et al., 1993; Benson et al., 2003). There are signs of fluctuating conditions around the LGM. Conditions wetter than present persisted into the early Holocene, even as temperatures increased. Earlier debates about the source of early Holocene moisture remain largely unresolved, although it appears that summer rainfall became established earlier in the Chihuahuan Desert than in the Sonoran Desert. Greater effective moisture in the early to mid-Holocene is attributed to increased summer precipitation driven by insolation forcing. By about 5000 BP, conditions seem to have become drier, with fully modern environments being established from about 4000 BP. There is some evidence for wetter conditions around 3000 to 2000 BP.

Over the last 1000 years, tree rings provide very high-resolution paleoclimatic data, and the number of records is increasing rapidly. Most of the records from northern Mexico come from Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco), with the longest sequence coming from Durango (AD 1376 to 1993). The Durango record from Cerro Baraja and El Salto (Fig. 5) (Acuna-Soto et al., 2002; Cleaveland et al., 2003) shows the importance of winter precipitation for soil moisture and subsequent tree growth, even in an area where summer rainfall dominates. It shows that persistent/recurrent La Niña conditions, with dry winters, lead to drought (for the trees). The most severe droughts in the record occurred between 1540 and 1579 (the "Megadrought," which was also associated with epidemics of hemorrhagic fever), in the 1860s, and in the 1950s (this major drought also affected the southern and southwestern U.S.A.). Relating the tree ring records to instrumental climate records and historical data has shown that tree rings respond to ENSO and to the onset and strength of the summer monsoon (Diaz et al., 2002; Therrell et al., 2002). Unfortunately, none of the other proxy records cover this time period or have this resolution.

TRANS-MEXICAN VOLCANIC BELT

This area is quite different from northern Mexico. It is geologically recent, is tectonically and volcanically active, and has long been a focus for human settlement. The tectonic disruption of a fluvial network has created a large number of lake basins, most of which still contain water (except where drained deliberately or affected by groundwater abstraction). As described above, a number of the highest peaks are still glaciated and a larger number were glaciated in the past. These offer an additional source of information (Fig. 6).

Lake sediments provide the greatest number of records from the TMVB (Fig. 6); these are mainly for the late Pleistocene and Holocene. To date, the records have been low resolution, partly because of sampling and dating, but also because there are few lakes that deposit laminated sediments. The interpretation of lake sediment records in terms of paleoclimate is affected by tephra deposition and the impact of long-term anthropogenic activity. Some pollen records have been interpreted in largely anthropogenic terms (Goman & Byrne, 1998). Previously published records reveal very complex patterns of change (Metcalfe et al., 2000; Caballero et al., 2002). In the late Pleistocene, there may be a contrast between the western part of the region (wetter than present) and the eastern part (drier than present) (Bradbury, 1997). The terminal Pleistocene seems to have been very dry in many areas, with wetter conditions being established in the early Holocene. There are indications of dry conditions around 5000 BP followed by more overall variability in climate in the second half of the Holocene. Many records show evidence for human impact on the environment over the last 3500 years, but there is some evidence for another dry episode around 1000 BP.

As in northern Mexico, there are few long climate records, but a 27 m core from Lake Cuitzeo (Fig. 6) may extend back more than 120,000 years (Israde et al., 2002). The present lake is highly alkaline and saline and has a maximum depth of less than 2 m. The age of the base of the core is only an estimate because the oldest ^{14}C date, 42,400 BP, is from 9 m. There are a number of substantial volcanic deposits in the core, including a 70-cm thick ash layer dating to around 25,000 BP. The base of the sequence (ca. 120 to 90,000 BP, equivalent to MIS 5) indicates a freshwater lake of moderate depth, with a lake transgression being indicated at the end of the period prior to the deposition of 10 m of silts, clays, and volcanic deposits. The mid-Pleistocene saw a brief deepening, followed by shallowing and increasing salinity. Around 35,000 BP, the lake was very low. After deposition of the 70 cm of ash, the lake became deeper again (around the LGM), but then shallowed. Pollen data (Velazquez Duran et al., 2001) reflect conditions wetter than present between 35,000 and 22,000 BP, with pollen of alder (*Alnus* Miller), hornbeam (*Carpinus* L.), hazel (*Corylus* L.), and willow (*Salix* L.). Unfortunately, there is a hiatus between ca. 17,650 and 8000 BP. This may reflect a dry period similar to that recorded in the northern part of the Basin of Mexico (Caballero et al., 1999), but recent isotope data for part of this period from another core from Cuitzeo indicate wet conditions. Very low lake level, with a possible hiatus, is indicated around 5000 BP, and the lake has been shallow and increasingly saline over the last 3000 years. These conditions seem to have been particularly pronounced over the last 1000 years. The record from Cuitzeo shows strong similarities to that from Babicora (see above), although conditions for the key period from the LGM into the early Holocene remain unresolved.

Lake Pátzcuaro is one of the best studied basins in the TMVB. Watts and Bradbury (1982) and Bradbury (2000) provide details of a record from the southern part of the lake covering the last 44,000 years. This indicated wet conditions in the basin in the full glacial and latest Pleistocene. Drying apparently only set in from the mid-Holocene, although the record was confused by human impact. Cores from the north and southwest of the basin (Metcalfe et al., in prep.) confirm the persistence of a relatively deep lake in the basin through the LGM and into the early Holocene. As in Babicora, a change in the dominant diatom taxa at the start of the Holocene seems to indicate a change in the seasonality of precipitation from winter-dominated to summer-dominated. The later Holocene record shows increased inputs of soil from the catchment, but analysis of δ^{18}O on authigenic carbonates and the occurrence of multiple ostracod layers show a number of episodes of drying. One of these episodes occurred shortly after AD 1342 to 1396 (calibrated ^{14}C date), corresponding to evidence for low lake level from an archaeological site in the southwestern part of the basin (Fisher et al., 2003) and to early documentary evidence for drought from the Basin of Mexico. From this basin, it is clear that lake sediment records have the potential to record climatic change of the recent past, but they must be interpreted with care.

Some of the highest peaks of the TMVB preserve records of glacial advance, although whether the glaciers in central Mexico responded to temperature or precipitation (or some combination of both) is still not clear. Early work on the area's glacial history was carried out in the 1950s and 1960s (e.g., White, 1962), with further studies by Heine (1988). Unfortunately, there was disagreement over both the identification of moraines and the timing of events. More recent work has used cosmogenic exposure dating (in situ ^{36}Cl), K-Ar, and dated tephras to improve the chronology (e.g., Vázquez Selem, 1998). It now appears that the maximum extent of glaciation of Iztaccihuatl occurred between about 150,000 and 126,000 BP (Vázquez Selem & Heine, 2004). This coincides with the high stand at Lake Cuitzeo. There were also advances (on Iztaccihuatl and the Nevado de Toluca, Fig. 6) in the late Pleistocene (including the LGM), when the equilibrium line altitude was about 1000 m below present. The Nevado de Toluca records readvance in the Younger Dryas (when conditions seem to have been relatively dry) and in the late Holocene. Global evidence from tropical glaciers suggests that cold conditions alone are not sufficient for glacial expansion (L. Thompson, pers. comm.); they must have some source of moisture. Given the location of Mexico's highest mountains, however, it is possible that at different times they could have received moisture from either tropical or midlatitude sources.

In many parts of the world, pollen records have played a key part in reconstructing climate change (Hooghiemstra, 2006). Unfortunately, pollen records from the TMVB have been difficult to interpret and are not always consistent with other proxies (Lozano García & Xelhuantzi López, 1997). They are also strongly affected by human activity in catchments. A pollen record from a very high altitude site (3860 m) avoids human impact and provides evidence of tree line fluctuations since the late Pleistocene (Lozano García & Vázquez Selem, 2005), reflecting the interaction of precipitation and temperature. The record indicates that the tree line was 700 to 500 m below present in the late Pleistocene/early Holocene. The forest expanded in the early mid-Holocene (ca. 6500 to 6000 BP) under warmer and wetter conditions, but was then replaced by grassland as the climate dried through to about 5000 BP. Wetter conditions are indicated about 3000 BP (by the presence of *Pinus hartwegii* Lindley), corresponding to the period of wetter conditions in northern Mexico and ice readvance on some on the peaks of the TMVB. Cooler and moister conditions are also indicated around 2000 BP. The location of this site close to the boundary between forest and alpine grassland makes it climatically sensitive. A similar picture of lowered treeline and an expansion of alpine grassland in the late Pleistocene has also been recorded in the Upper Lerma basin (2570 m) (Lozano García et al., 2005). Sites at lower altitudes in the TMVB appear not to be as climatically sensitive and are more likely to be affected by human activity through the Holocene.

The late Holocene climatic variability indicated by lake and bog records is also confirmed by tree ring records emerging from this part of Mexico. The TMVB and states immediately to the north (e.g., San Luis Potosi) have recently become a focus for dendroclimatology. Records from this area seem to be most sensitive to summer precipitation (unlike those from Durango, see above). A climatic record from Douglas fir tree rings from Cuauhtemoc La Fragua, Puebla (Stahle et al., 2003), covering the period AD 1474 to 2001 has been correlated with maize (*Zea mays* L.) yields. Seven periods of low yield coincide with drought, famine, and social unrest. Tree ring records clearly have considerable potential, especially when combined with historical records (Therrell et al., 2004), to extend our knowledge of climate change back from the rather short-term instrumental records and forward from the more traditional geological archives. Even tree ring records, however, are not immune from human impact. A Montezuma bald cypress (*Taxodium mucronatum* Tenore) record from Chapultepec Park in the center of Mexico City (Villanueva-Diaz et al., 2003) appears to lose its climate/ring width relationship over the last 80 years as a result of effects of groundwater abstraction.

There is still little evidence from the TMVB for conditions in the last interglacial period, but there is some indication that it was wet. The mid-Pleistocene may also have been wetter than the late Pleistocene; this contrasts with the situation in northern Mexico. The pattern of conditions at the LGM still remains unclear because more records are needed from west of 101°W to confirm that it was indeed wetter, while the east was drier. Records from the Basin of Mexico indicate very dry conditions in the late glacial and early Holocene, but again there are few other records for comparison. Pátzcuaro was clearly not dry over this period. The patterns of change over the Holocene indicated by earlier studies have generally been confirmed with drier conditions around 5000 BP and again about 1000 to 900 BP.

SUMMARY

Pleistocene conditions in Mexico were clearly very different from present conditions. Northern Mexico was much more forested (pinyon-juniper woodland, chaparral), with extensive lakes and wetland areas. In some areas, this woodland persisted for at least 30,000 years before the establishment of the modern desert scrub vegetation in the early to mid-Holocene (Van Devender, 1990b). The balance of evidence indicates that increased moisture was brought by westerly winds bringing more winter precipitation farther south than today. In central Mexico, glaciers and alpine grasslands expanded, and there were extensive forests of pine, oak, spruce, and alder. Evidence from farther south in Mexico, the Caribbean, and northern South America clearly indicates that the summer rainfall regime had largely broken down; therefore, it seems likely that some moisture reached this area from midlatitudes. Whether this was sufficient to drive higher lake levels in the west of Mexico and explains the expansion of glaciers on Mexico's highest peaks remains to be established. A transition toward the modern climate regime occurred about 9000 BP as the north of Mexico started to dry out. Pinyon-juniper woodlands retreated north, and spruce (*Picea*) died out. In the central highlands, very dry conditions are recorded in the Basin of Mexico, but there is little clear evidence from other sites. The early to mid-Holocene was warmer and wetter than present in both the TMVB and northern Mexico, presumably due to an enhanced summer monsoon in response to the insolation maximum. From about 4000 BP, modern desert conditions (desert scrub and succulents) became established in the north, and subtropical elements entered the TMVB (again, as

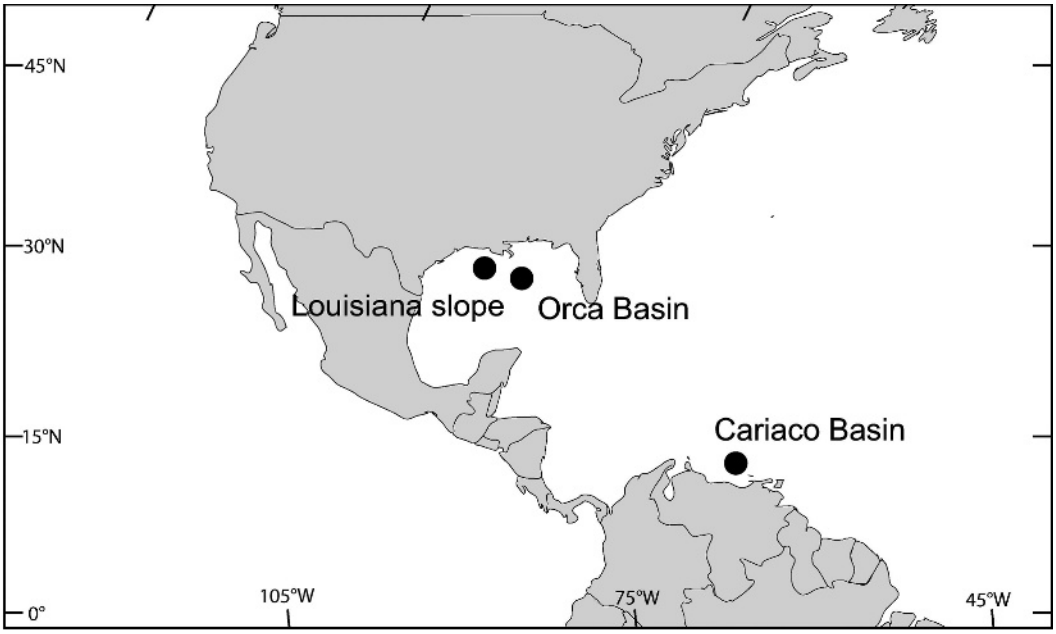

Figure 7. Locations of deep sea cores in the Gulf of Mexico and Caribbean basin referred to in the text.

present). Strong variability seems to mark the later Holocene, but many records from the north do not cover this period (no deposition or lack of preservation); furthermore, in the central highlands, records are confounded by human disturbance.

CAN WE IDENTIFY THE CAUSES OF CLIMATE CHANGE?

Changes in insolation (Milankovitch forcing), sea-surface temperature, the extent and height of the Laurentide ice sheet, and CO_2 concentrations have all been identified as possible drivers of climatic and vegetation change over the late Quaternary. There is also increasing interest in the timing and magnitude of ENSO, or ENSO-type, events and their impact on Holocene climate change. The inevitably patchy terrestrial records of change provide some indication of the role of these forcings. Evidence for the influence of insolation and the Laurentide ice sheet is clear from the literature, and CO_2 concentrations have played some role in vegetation change, at least regionally (Huang et al., 2001). Some further evidence can be derived from deep sea cores from the Gulf of Mexico/tropical Atlantic (Fig. 7). Results from the Orca basin and Louisiana slope (Broecker et al., 1989; Poore et al., 2003) have shown pulses of meltwater from the Laurentide ice sheet entering the Gulf of Mexico periodically from as early as 16,000 years ago. The occurrence of three major pulses in the late glacial period has been well established (Kennett et al., 1985), but Aharon's (2003) study shows renewed inputs of meltwater between about 9900 and 8900 years ago. These inputs may help to explain why the summer rainfall regime in the circum-Caribbean region did not become fully established until the early Holocene, lagging the insolation forcing. Hence, the influence of the Laurentide ice sheet has to be considered both through its rearrangement of upper air circulation and the impacts of its meltwater. While meltwater entering the Gulf of Mexico might seem the most likely to have affected the climate of Mexico, an increasing number of records (including those from the Gulf of California) indicate that meltwater pulses into the North Atlantic (Heinrich events) also had an effect on the Mexican climate.

Some of the most detailed ocean records have been obtained from the Cariaco Basin off the coast of Venezuela (Fig. 7), where upwelling results in laminated sediments. Haug et al. (2001) report evidence from the Cariaco Basin for shifts in the location of the ITCZ since the last glacial period. Concentrations of Ti in the sediments are used as a proxy for runoff from the adjacent land, which itself responds to the changing location of the ITCZ driven by insolation and ENSO. The long-term record shows runoff increasing in the early Holocene as the ITCZ moved north in response to insolation, but then decreasing from the mid-Holocene as the ITCZ returned southward. At this time, drying occurred in the Caribbean, central and northern Mexico, and tropical north Africa. Dry events are recorded in the Younger Dryas and at 8200 BP in response to cooling in the North Atlantic. At higher resolution, the record shows the importance of the equatorial Pacific through the onset of stronger ENSOs from about 5000 BP (also seen in the Guymas Basin). The impact of ENSO is seen in the position of the ITCZ, which lies farther to the north in La Niña years and farther to the south in El Niño years. At the highest resolution, annual variations in insolation occur on time scales of the solar cycles (e.g., 11, 22 years). These solar cycles have also been detected in lake sediment records from the Yucatan peninsula (Hodell et al., 2001).

Conclusions

A number of important questions relating to the nature and timing of late Quaternary climatic change in northern and central Mexico remain unresolved. In some cases, it may simply be a matter of working on more sites to try to fill some of the gaps in our knowledge. Late glacial and early Holocene conditions were very strongly influenced by the Laurentide ice sheet and its history. Reorganizations of the major features of the atmospheric circulation in the late Pleistocene led to major changes in seasonality and amount of precipitation. These changes in precipitation were reflected by significant changes in vegetation distribution, bringing together assemblages of plants not found together today. Evidence for early warming seems to be recorded in some deep sea core records, but is not apparent in the terrestrial records. The modern summer rainfall regime only became fully established after 9000 BP, and the early Holocene was probably wetter over wide areas than today. Changes through the Holocene are consistent with insolation forcing, the resulting position of the ITCZ, and enhanced monsoon precipitation (Harrison et al., 2003; Ruter et al., 2004). So far, only deep sea core records show the onset of the modern ENSO regime from the mid-Holocene, although many different types of proxies show increased climatic variability after this time. Only the highest resolution records (annually laminated deep sea cores and tree rings) show ENSO and solar cycles.

It is clear that we still need better understanding of what drives change in many of the systems from which we derive our paleoclimatic records (e.g., vegetation, glaciers, lake levels). Better monitoring in the present day would help, but it does seem that there may be no analogues for conditions at certain periods in the past. The better integration of terrestrial and marine records should improve our understanding, but as the examples from the Gulf of California indicate, this is not always a straightforward task. Obtaining continuous, long, high-resolution terrestrial records would facilitate this comparison. For the more recent past, the integration of proxy records with historical and instrumental data could shed more light on both the nature of climatic variability and the ways in which human societies have coped (or not) with the vagaries of the climate system.

Literature Cited

Acuna Soto, R., D. W. Stahle, M. K. Cleaveland & M. D. Therrell. 2002. Megadrought and megadeath in 16th century Mexico. Emerg. Infect. Dis. 8: 360–362.

Aharon, P. 2003. Meltwater flooding events in the Gulf of Mexico revisited: Implications for rapid climate changes during the last deglaciation. Paleoceanog. 18(4): art. no. 1079. doi:10.1029/2002PA000840,2003.

Anderson, R. S. & T. R. Van Devender. 1995. Vegetation history and paleoclimates of the coastal lowlands of Sonora, Mexico—Pollen records from pack-rat middens. J. Arid Environm. 30: 295–306.

Barron, J. A., D. Bukry & J. L. Bishoff. 2004. High resolution paleoceanography of the Guaymas Basin, Gulf of California, during the past 15,000 years. Mar. Micropaleontol. 50: 185–207.

Benson, L., S. Lund, R. Negrini, B. Linsley & M. Zic. 2003. Response of North American Great Basin lakes to Dansgaard-Oeschger oscillations. Quatern. Sci. Rev. 22: 2239–2251.

Betancourt, J. L., K. Aasen Rylander, M. C. Peñalba & J. L. McVikar. 2001. Late Quaternary vegetation history of Rough Canyon, south-central New Mexico, U.S.A. Palaeogeogr. Palaeoclimatol. Palaeoecol. 165: 71–95.

Bradbury, J. P. 1997. Sources of glacial moisture in Mesoamerica. Quatern. Int. 43/44: 97–110.

———. 2000. Limnologic history of Lago de Pátzcuaro, Michoacán, Mexico for the past 48,000 years: Impacts of climate and man. Palaeogeogr. Palaeoclimatol. Palaeoecol. 163: 69–95.

———, M. Grosjean, S. Stine & F. Sylvestre. 2000. Full and late glacial lake records along the PEP1 transect: Their role in developing interhemispheric paleoclimatic interactions. Pp. 265–291 *in* V. Markgraf (editor), Interhemispheric Climate Linkages. Academic Press, San Diego.

Brito Castillo, L., S. Díaz Castro, C. A. Salinas Zavala & A. V. Douglas. 2003. Reconstruction of long-term winter streamflow in the Gulf of California watershed. J. Hydrol. 278: 39–50.

Broecker, W. S. et al. (+ 6 authors). 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature 341: 318–321.

Caballero, M., S. Lozano, B. Ortega, J. Urrutia & J.-L. Macias. 1999. Environmental characteristics of Lake Tecocomulco, northern Basin of Mexico, for the last 50,000 years. J. Paleolimnol. 22: 399–411.

———, B. Ortega, F. Valdez, S. Metcalfe, J-L. Macias et al. 2002. Sta. Cruz Atizapan: A 22-ka lake level record and climatic implications for the late Holocene human occupation in the Upper Lerma Basin, Central Mexico. Palaeogeogr. Palaeoclimatol. Palaeoecol. 186: 217–235.

Castiglia, P. & P. J. Fawcett. 2001. Shoreline and lacustrine records of late Quaternary climate change in the Chihuahuan desert, Mexico. Eos Trans. 82: 78.

——— & ———. 2006. Large Holocene lakes and climate change in the Chihuahuan desert. Geology 34: 113–116.

Cleaveland, M. K., D. W. Stahle, M. D. Therrell, J. Villanueva-Diaz & B. T. Burns. 2003. Tree-ring reconstructed winter precipitation and tropical teleconnections in Durango, Mexico. Climatic Change 59: 369–388.

COHMAP Members. 1988. Climatic changes of the last 18,000 years: Observations and model simulations. Science 241: 1043–1052.

Diaz, S. C., M. D. Therrell, D. W. Stahle & M. K. Cleaveland. 2002. Chihuahua (Mexico) winter-spring precipitation reconstructed from tree-rings, 1647–1992. Clim. Res. 22: 237–244.

Douglas, M. W., R. A. Maddox, K. Howard & S. Reyes. 1993. The Mexican monsoon. J. Climate 6: 1665–1677.

Englehart, P. & A. R. Douglas. 2001. The role of eastern north Pacific tropical storms in the rainfall climatology of western Mexico. Int. J. Climatol. 21: 1357–1370.

Fisher, C. T., H. P. Pollard, I. Israde-Alcantara, V. H. Garduño-Monroy & S. K. Banerjee. 2003. A reexamination of human-induced environmental change within the Lake Pátzcuaro Basin, Michoacan, Mexico. Proc. Natl. Acad. Sci. U.S.A. 100: 4957–4962.

Fritz, S. C., S. E. Metcalfe & W. Dean. 2001. Holocene climate patterns in the Americas inferred from paleolimnological records. Pp. 241–263 *in* V. Markgraf (editor), Interhemispheric Climate Linkages. Academic Press, San Diego.

Gasse, F. 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. Quatern. Sci. Rev. 19: 189–211.

Goman, M. & R. Byrne. 1998. A 5000-year record of agriculture and tropical forest clearance in the Tuxtlas, Veracruz, Mexico. Holocene 8: 83–89.

Harrison, S. P. et al. (+ 7 authors). 2003. Mid-Holocene climates of the Americas: A dynamical response to changes in seasonality. Clim. Dynam. 20: 663–688.

Haug, G. H., K. A. Hughen, D. M. Sigman, L. C. Peterson & U. Rohl. 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. Science 293: 1304–1308.

Heine, K. 1988. Late Quaternary glacial chronology of the Mexican volcanoes. Geowissenschaften 7: 197–205.

Higgins, R. W., K. C. Mo & Y. Yao. 1998. Interannual variability of the U.S. summer precipitation regime with emphasis on the southwestern monsoon. J. Climate 11: 2582–2606.

——— et al. (+ 16 authors). 2003. Progress in Pan American CLIVAR research: The North American monsoon system. Atmosfera 16: 29–65.

Hodell, D. A., M. Brenner, J. H. Curtis & T. Guilderson. 2001. Solar forcing of drought frequency in the Maya lowlands. Science 292: 1–4.

Holmgren, C. A., M. C. Peñalba, K. A. Rylander & J. L. Betancourt. 2003. A 16,000 C-14 yr BP packrat midden series from the U.S.A.–Mexico borderlands. Quatern. Res. 60: 319–329.

Hooghiemstra, H. 2006. Quaternary vegetational history at the extremes: The High Andes and Amazonia. Ann. Missouri Bot. Gard. 93: 297–324.

Huang, Y. et al. (+ 5 authors). 2001. Climate change as the dominant control on glacial-interglacial variations in C_3 and C_4 plant abundance. Science 293: 1647–1651.

Israde Alcantara, I., V. H. Garduño Monroy & R. Ortega Murillo. 2002. Paleoambiente lacustre del cuaternario tardío en el centro del lago de Cuitzeo. Hidrobiol. 2: 61–78.

Kennett, J. P., K. Elmstrom & N. L. Penrose. 1985. The last deglaciation in the Orca basin, Gulf of Mexico: High resolution planktonic foraminifera changes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 50: 189–216.

Lozano García, S. & M. S. Xelhuantzi López. 1997. Some problems in the Late Quaternary pollen records of central Mexico: Basin of Mexico and Zacapu. Quatern. Int. 43/44: 117–123.

——— & L. Vázquez Selem. 2005. A high elevation Holocene pollen record from Iztaccihuatl volcano, central Mexico. Holocene 15: 329–338.

———, B. Ortega Guerrero & S. Sosa Nájera. 2002. Mid- to late-Wisconsin pollen record of San Felipe Basin, Baja California. Quatern. Res. 58: 84–92.

———, S. Sosa Nájera, Y. Sugiera & M. Caballero. 2005. 23,000 yr of vegetation history of the Upper Lerma, a tropical high-altitude basin in Central Mexico. Quatern. Res. 64: 70–82.

Magaña, V. O., J. L. Vazquez, J. L. Perez & J. B. Perez. 2003. Impact of El Niño on precipitation in Mexico. Geofis. Int. 42: 313–330.

McAuliffe, J. R. & T. R. Van Devender. 1998. A 22,000-year record of vegetation change in the north-central Sonoran Desert. Palaeogeogr. Palaeoclimatol. Palaeoecol. 141: 253–275.

Metcalfe, S., A. Say, S. Black, R. McCulloch & S. O'Hara. 2002. Wet conditions during the last glaciation in the Chihuahuan desert, Alta Babicora Basin, Mexico. Quatern. Res. 57: 91–101.

Metcalfe, S. E., S. L. O'Hara, M. Caballero & S. J. Davies. 2000. Records of Late Pleistocene-Holocene climatic change in Mexico—A review. Quatern. Sci. Rev. 19: 699–721.

Meyer, E. R. 1973. Late-Quaternary paleoecology of the Cuatro Cienegas Basin, Coahuila, Mexico. Ecology 54: 982–995.

Mosiño Aleman, P. A. & E. García. 1974. The climate of Mexico. Pp. 345–405 *in* R. A. H. Bryson & F. K. Hare (editors), Climates of North America, Vol. 2. Elsevier, New York.

Moy, C. M., G. O. Seltzer, D. T. Rodbell & D. M. Anderson. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature 420: 162–165.

Ortega Guerrero, B., M. Caballero Miranda, S. Lozano García & M. De la O Villanueva. 1999. Palaeoenvironmental record of the last 70,000 yr in San Felipe Basin, Sonora desert, Mexico: Preliminary results. Geofis. Int. 38: 1–11.

Ortega Ramirez, J., A. Valiente Banuet, J. Urrutia Fucugauchi, C. Mortera Gutierrez & G. Alvarado Valdez. 1998. Paleoclimatic changes during the Late Pleistocene–Holocene in Laguna Babicora, near the Chihuahuan Desert, Mexico. Canad. J. Earth Sci. 35: 1168–1179.

Palacios-Fest, M., A. L. Carreno, J. Ortega-Ramirez & G. Alvarado-Valdez. 2002. A palaeoenvironmental reconstruction of laguna Babicora, Chihuahua, Mexico, based on ostrocod palaeoecology and trace element shell chemistry. J. Paleolimnol. 27: 185–206.

Peñalba, M. C. & T. R. Van Devender. 1997. Pollen analysis of Late Wisconsin and Holocene packrat (Neotoma) middens from San Fernando and Catavina, Baja California. Botanical Symposium, Symposium Abstracts: Peinado to Zirahuen. San Diego Natural History Museum, San Diego.

Pike, J. & A. E. S. Kemp. 1997. Early Holocene decadal-scale ocean variability recorded in Gulf of California laminated sediments. Paleoceanog. 12: 227–238.

Poore, R. Z., H. J. Dowsett & S. Verardo. 2003. Millennial- to century-scale variability in Gulf of Mexico Holocene climate records. Paleoceanog. 18(2): art. no. 1048. doi:10.1029/2002PA000868,2003.

Rhode, D. 2002. Early Holocene juniper woodland and chaparral taxa in the Central Baja California peninsula, Mexico. Quatern. Res. 57: 102–108.

Rodbell, D. T. et al. (+ 5 authors). 1999. An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. Science 283: 516–520.

Ruter, A., J. Arzt, S. Vavrus, R. A. Bryson & J. E. Kutzbach. 2004. Climate and environment of the subtropical and tropical Americas (NH) in the mid-Holocene: Comparison of observations with climate model simulations. Quatern. Sci. Rev. 23: 663–679.

Rzedowski, J. 1973. Geographical relationships of the flora of Mexican dry regions. Pp. 61–72 *in* A. Graham (editor), Vegetation and Vegetational History of Northern Latin America. Elsevier, New York.

———. 1994. Vegetación de México. Limusa, Mexico DF.

Sancetta, C. 1995. Diatoms in the Gulf of California—Seasonal flux patterns and the sediment record for the last 15,000 years. Paleoceanog. 10: 67–84.

Stahle, D. W. & M. K. Cleaveland. 1993. Southern oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and southern Great Plains. J. Climate 6: 129–140.

———, M. D. Therrell, J. Villanueva-Diaz & E. H. Cornejo-Oviedo. 2003. El bosque centenario de Abeto Douglas (*Pseudotsuga menziesii*) cerca de Cuauhtemoc La Fragua, Puebla, Mexico. Unpublished manuscript.

Therrell, M. D., D. W. Stahle, M. K. Cleaveland & J. Villanueva-Diaz. 2002. Warm season tree growth and precipitation over Mexico. J. Geophys. Res. 107(D14): art. no. 4205. doi:10.1029/2001JD000851,2002.

———, ——— & R. Acuna Soto. 2004. Aztec drought and the "Curse of One Rabbit. Bull. Amer. Meteorol. Soc. (September): 1–10.

Thompson, R. S., C. Whitlock, P. J. Bartlein, S. P. Harrison & W. G. Spaulding. 1993. Climatic changes in the western United States since 18,000 yr BP. Pp. 318–356 *in* H. E. Wright, J. E. Kutzbach & T. WebbIII (editors), Global Climates Since the Last Glacial Maximum. Univ. Minnesota Press, Minneapolis.

Tudhope, A. W. et al. (+ 8 authors). 2001. Variability in the El Niño–Southern oscillation through a glacial-interglacial cycle. Science 291: 1511–1517.

Van Devender, T. R. 1990a. Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico. Pp. 134–165 *in* J. L. Betancourt, T. R. Van Devender & P. S. Martin (editors), Packrat Middens: The Last 40,000 years of Biotic Change. Univ. Arizona Press, Tucson.

———. 1990b. Late Quaternary vegetation and climate of the Chihuahuan Desert, United States and Mexico. Pp. 104–133 *in* J. L. Betancourt, T. R. Van Devender & P. S. Martin (editors), Packrat Middens: The Last 40,000 Years of Biotic Change. Univ. Arizona Press, Tucson.

———. 1997. 21,000 years of vegetation change in the northern Vizcaino Norte, Baja California. Botanical Symposium Abstracts, San Diego Natural History Museum, San Diego.

——— & T. L. Burgess. 1985. Late Pleistocene woodlands in the Bolson de Mapimi: A refugium for the Chihuahuan desert biota? Quatern. Res. 24: 346–353.

———, T. L. Burgess, R. S. Felger & R. M. Turner. 1990. Holocene vegetation of the Hornaday Mountains of the northwest Sonora, Mexico. Proc. San Diego Soc. Nat. Hist. 2: 1–19.

Vázquez Selem, L. 1998. Glacial chronology of Iztaccihuatl volcano, central Mexico, based on cosmogenic ^{36}Cl exposure ages and tephrochronology [abstract]. American Quaternary Association, Puerto Vallarta, Mexico.

——— & K. Heine. 2004. Late Quaternary glaciation in Mexico. Pp. 233–242 *in* J. Ehlers & P. L. Gibbard (editors), Quaternary Glaciations—Extent and Chronology, Part III. South America, Asia, Africa, Australia, Antarctica. Elsevier, Amsterdam.

Velázquez Duran, R., I. Israde Alcantare & S. Lozano García. 2001. Significado ecológico de los palinomorfos depositados en el lago de Cuitzeo, Michoacán, durante los últimos 35,000 anos. Ci. Nicolaita 29: 45–61.

Villanueva Diaz, J. et al. (+ 8 authors). 2003. Registros climáticos de los Ahuehuetes de Chapultepec en los ultimos 450 años. Bol. Arch. Hist. Agua (January–April): 34–43.

Watts, W. A. & J. P. Bradbury. 1982. Paleoecological studies at Lake Pátzcuaro on the west-central Mexican Plateau and at Chalco in the Basin of Mexico. Quatern. Res. 17: 56–70.

White, S. E. 1962. Late Pleistocene glacial sequence for the west side of Iztaccihuatl, Mexico. Geol. Soc. Amer. Bull. 73: 935–958.