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Late Quaternary evolution of alluvial fans in the Playa, El Fresnal region, northern Chihuahua desert, Mexico: Palaeoclimatic implications

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RESUMEN

Estudios multidisciplinarios de geología del Cuaternario, ecología y geofísica en la región que actualmente ocupa el Lago-Playa El Fresnal, norte del estado de Chihuahua, indican que se trata de una cuenca en extensión de tipo medio-graben, caracterizada por un lago-playa en la parte basal, rodeado por piemontes cubiertos por abanicos aluviales. El tectonismo extensional produjo zonas de fallas normales, bloques basculados con expresiones geomórficas diferenciales y volcanismo. El área del bloque levantado es la fuente principal de aportes detríticos; sin embargo, debido a la naturaleza asimétrica de la cuenca, los sedimentos provenientes del bloque hundido se encuentran espacialmente más distribuidos. Resultado del basculamiento, los abanicos aluviales se segmentaron quedando las superficies más antiguas en la parte distal del bloque levantado y en la parte proximal del bloque hundido.

Hasta ahora, la evolución de los abanicos aluviales ha sido considerada como el resultado de las variables tectónicas y climáticas; sin embargo, la función e importancia relativa que éstas tienen en el control de la sedimentación tanto de los abanicos aluviales como de los rellenos de la cuenca no ha sido aún resuelto. Por ejemplo, algunos autores enfatizan la influencia de los cambios climáticos, mientras que otros ponderan el efecto de la actividad tectónica. En el presente trabajo se analizan los aspectos geomorfológicos de los abanicos aluviales, su posición topográfica relativa, el grado de disección y desarrollo de suelos, el tipo de drenaje, y de manera general, las distintas facies sedimentarias. Nuestros resultados indican que en la región existen tres generaciones de abanicos aluviales, formados durante las principales variaciones climáticas del Cuaternario Tardío. Esta interpretación es consistente con los principales cambios climáticos registrados en la estratigrafía paleolacustre del norte de México y del suroeste de los Estados Unidos. Los abanicos aluviales están formados principalmente por depósitos de tipo debris-flow, resultado de precipitaciones abundantes de corta duración, producidas probablemente por cambios en las condiciones climáticas de relativamente húmedas a áridas. Las facies sedimentarias de estos depósitos contrastan con las producidas por regímenes típicamente fluviales.

PALABRAS CLAVE: Abanicos aluviales, Cuaternario Tardío, cambios climáticos, Playa El Fresnal, tectonismo extensional, desierto Chihuahuense.

ABSTRACT

The Playa El Fresnal area is a tilted terrane characteristic of an extensional basin. It is a half graben/tilted-block system with a playa-lake on the basin floor flanked by piedmonts covered by alluvial fans. Structural heterogeneities within normal fault zones influenced the geomorphic expression of the uplifted footwall blocks of associated volcanism, and the downdropped hanging wall. The footwall area is the main sediment source, but the hanging wall-derived sediments are more extensive. The ancient alluvial fans are in the distal part, whereas the hanging-wall sediments are located in the apex area.

A geomorphic analysis of the relative topographic position of the alluvial fans, degree of dissection of the original surfaces, general sedimentology (facies description), and stream channel network type, highlights the importance of climatic change in interpreting alluvial-fan surfaces. Three generations of alluvial fans were identified on the footwall and hanging wall slopes. They were formed during the late Quaternary climatic shift, consistent with the main climatic changes recorded in the paleolake stratigraphy of northern Mexico and the American Southwest. These alluvial fans consist mainly of debris-flow deposits from flash floods, probably triggered by a change from relatively moist to arid conditions. They contrast with the typically lower-flow-regime of thick-bedded, cross-bedded, and lenticular channel facies, and associated floodplain sequences of rivers.

KEY WORDS: alluvial fans, late Quaternary climate change, Playa El Fresnal, extensional tectonism, Chihuahuan desert.

1. INTRODUCTION

Playa El Fresnal is one of many north to north-west-trending, tectonically active extensional basins in northern Mexico and the southwestern United States. It has the geomorphic expression of many bolsones of the Basin and Range physiographic province (Morrison, 1991; Gile *et al.*, 1981). It is considered the southernmost expression of the Río Grande Rift (Seager and Morgan, 1979; Morrison, 1991), and it developed after the Oligocene (Chapin and Seager, 1975; Morrison, 1991; Mack *et al.*, 1994). Tectonism produced intermittently through Pliocene and into Quaternary time a series of fault-block ranges with active range-bounding normal fault systems (Chapin and Seager, 1975; Bachman and Mehnert, 1978; King and Ellis, 1990), associated volcanism, and basin subsidence (Muehlberger *et al.*, 1978; Seager *et al.*, 1984; Gustavson, 1991) (Figure 1). In the late Tertiary, this area consisted of two separated basins, the Palomas-Mimbres-Los Muertos basin and the Hueco bolson basin located in New Mexico and Texas, respectively (Seager and Morgan, 1979; Stuart and Willingham, 1984; Mack *et al.*, 1997) (Figure 2 A). The Palomas-Mimbres-Los Muertos basin extends into northern Mexico and includes Lake Palomas, Bolson de Los Muertos, Playa Guzmán, the Santa María, and Fresnal playas (Reeves, 1965, 1969; Stuart and Willingham, 1984; Mack *et al.*, 1997) (Figure 2 B). During the late Pleistocene and Holocene tectonism and climate changes were operating together (Chapin and Seager, 1975; Morrison, 1991; Mack *et al.*, 1994). The number, magnitude and duration of climatic events are inferred from the depth of stream cuttings, areas of alluviation, and alluvial landforms (Kottlowski *et al.*, 1965).

Tectonism and climate are the primary variables considered in studies of the evolution of Quaternary alluvial fans (e.g., Wells *et al.*, 1987; Ritter *et al.*, 1995; Campos-Enríquez

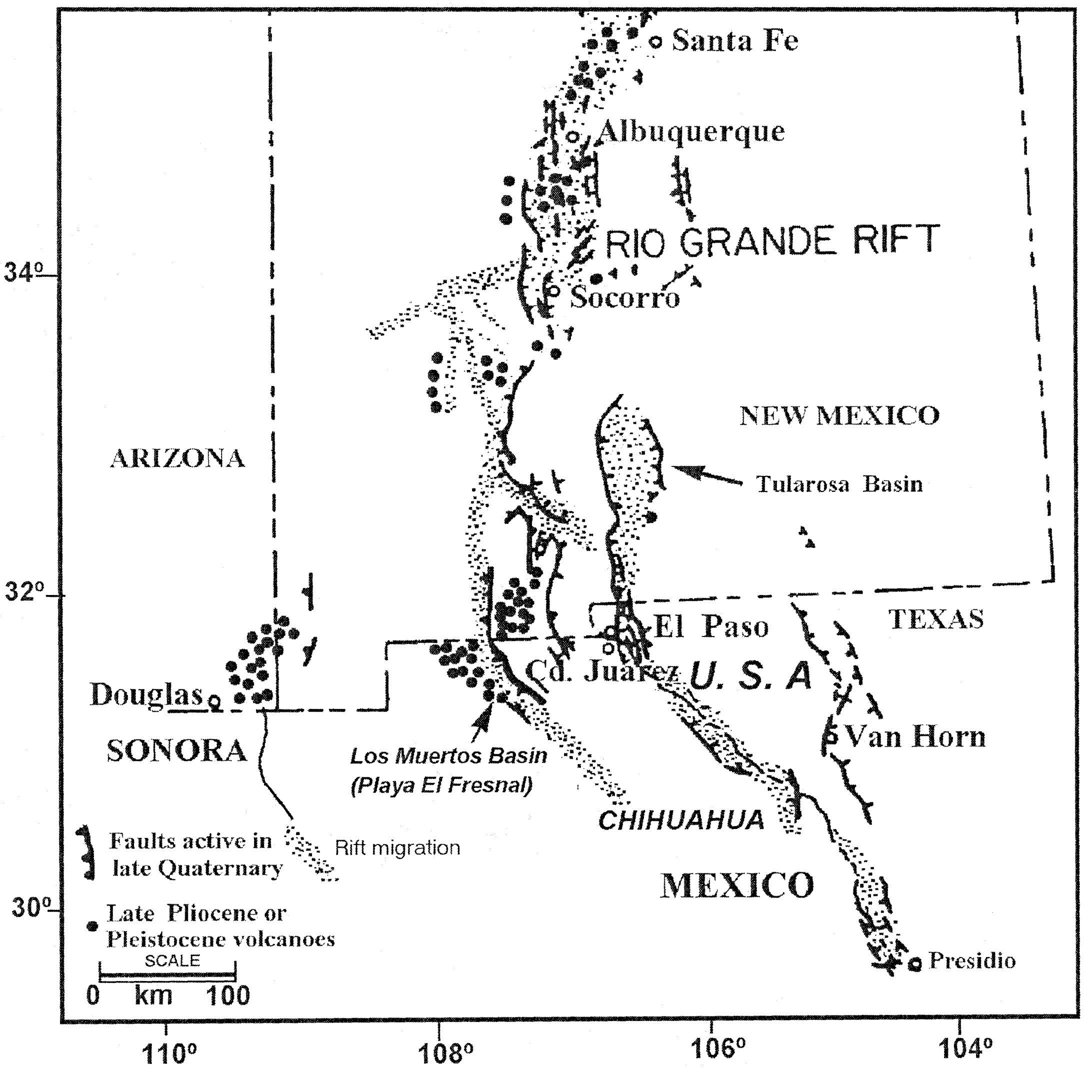

Fig. 1. Map showing the relation of late Quaternary faults and late Pliocene and Pleistocene volcanoes of the Río Grande rift (Modified from Seager and Morgan, 1979).

et al., 1999). However, their respective role and relative importance with respect to fan aggradation, progradation, entrenchment, and the sedimentological processes that affect fans are not fully resolved. Alluvial-fan sedimentation may occur during a climatic change inducing changes in mass availability and mass transfer processes, e.g. the glacial-interglacial cycle when the climate is cool and effectively wet (Dorn *et al.*, 1987; Harvey, 1987), or when the climate is in transition from cool to warm (Bull and Schick, 1979), or when the climate is warm and effectively dry (Bull, 1991; Reheis *et al.*, 1996), or when the climate changes from dry to wet (McFadden and McAuliffe, 1997; Waters and Haynes, 2001).

A well-documented example of this paleoclimatic approach was proposed by Reheis *et al.* (1996) for Fishlake Valley, Nevada and California, where a virtual shutdown of fan deposition and development of thick draping soils during the late Pleistocene glacial maximum was interpreted in terms of fan surfaces essentially bypassed as fan channels incised in response to reduced sediment supply and increased runoff. Another example in early Holocene was the decrease in effective precipitation which initiated time-transgressive changes in plant communities and diminished hill slope vegetation densities that, in turn, affected runoff-infiltration regimes, sediment availability and yield, eolian dust input, and soil moisture regimes. The trend to higher temperatures, aridity, and dominance of summer convective precipitation caused a substantial rise of the tree line and an increase in the incidence of widespread progradation of coarse-grained alluvial fans in response to the poorly vegetated catchment slopes onto alluvial fans (Bull and Schick, 1979; Wells *et al.*, 1987; Bull, 1991; Leeder *et al.*, 1998).

Disagreement exists as to whether climate or tectonics is the primary regulator of mass availability in the source area and of mass transfer to the alluvial fans. Davis (1905) and Blissenbach (1954) emphasized the role of faulting in initiating erosion in the source area and the aggradation of fans; but Beaty (1961) and Bull (1964, 1977) related tectonism to fan morphology including segmented radial fan profiles, incision of the fan-head and the development of complex fans. Another controversial aspect of alluvial-fan formation is related to the relative role of climate and tectonics in controlling fan sedimentation and the interaction between fan and basin-floor depositional systems (e.g., Leeder and Gawthorpe, 1987; Bull, 1991; Reheis *et al.*, 1996). It seems useful to consider climatic and tectonic variables together, rather than separately, when investigating complex topographic forms where fan source areas have undergone both varying degrees of tectonic activity and climate change, such as the Pleistocene/Holocene transition and the early Holocene paleoclimatic changes. Understanding how climate change controlled the alluvial-fan sedimentation process, independently of regional variations in tectonic activity, is essential for predicting the impact of future climate changes on geomorphic processes, on land use, and for deciphering the geomorphic and stratigraphic record of climate change in surficial formations. This, in turn, may indirectly provide information on the reserves of shallow aquifers since the ground-water system responds to climate changes in late Pleistocene and Holocene times.

The Playa el Fresnal area was chosen for morphostratigraphic analysis because it contains tilted fault-block mountains resulting in basin asymmetry and transverse elements that reflect both climatic and tectonic influences. This study is a continuation of those of Ortega-Ramírez *et al.*, (2001) and Bandy *et al.*, (2002), whose focus was on the effects of tectonics as a primary regulator of mass availability in the source area and mass transfer to alluvial fan, and the basin geometry and the depth of the sediment infill, respectively.

Here, we include the role of climate in the formation of alluvial fans related to the paleoclimatic history of the landform, and the relative influences of environmental factors on the evolution of the alluvial fans in the Playa El Fresnal region. The goals of this study are: (1) to refine the surficial stratigraphy of the alluvial fan deposits; and, (2) to relate the relative stratigraphy of the alluvial fans to geomorphic features and deposits associated with paleoclimatic changes and to compare it to that developed regionally by other researchers, under the assumption that if regional climate has changed, then it may be possible to infer global climate change variation thought the late Quaternary that affected this presently arid region.

The methods of study include: characterization of the catchment drainage net and geology using available aerial photographs (1:70,000 scale) and topographic maps (scale 1:50,000, 20 m contour interval), mapping morpho-stratigraphic units that were initially delineated on the aerial photographs; characterization of sedimentary facies through study of stream-bank exposures and shallow excavations. The stratigraphy has been defined on the basis of topography, stratigraphic relationships, development of soil profiles, and morphology of fan surfaces. Relative-age methods, in particular the phases of development for alluvial fans proposed by Bull (1977) and the degree of dissection of the original surfaces, sedimentary structures, and drainage pattern (Hunt and Mabey, 1966; Christenson and Purcell, 1985), have been used to characterized geomorphic surfaces. Relative differences in age between map units have been substantiated by field descriptions of the development of soil profiles.

2. REGIONAL SETTING

The study area is located in the northern part of the state of Chihuahua, Mexico, at 31° 05'N and 107°30'W. It is

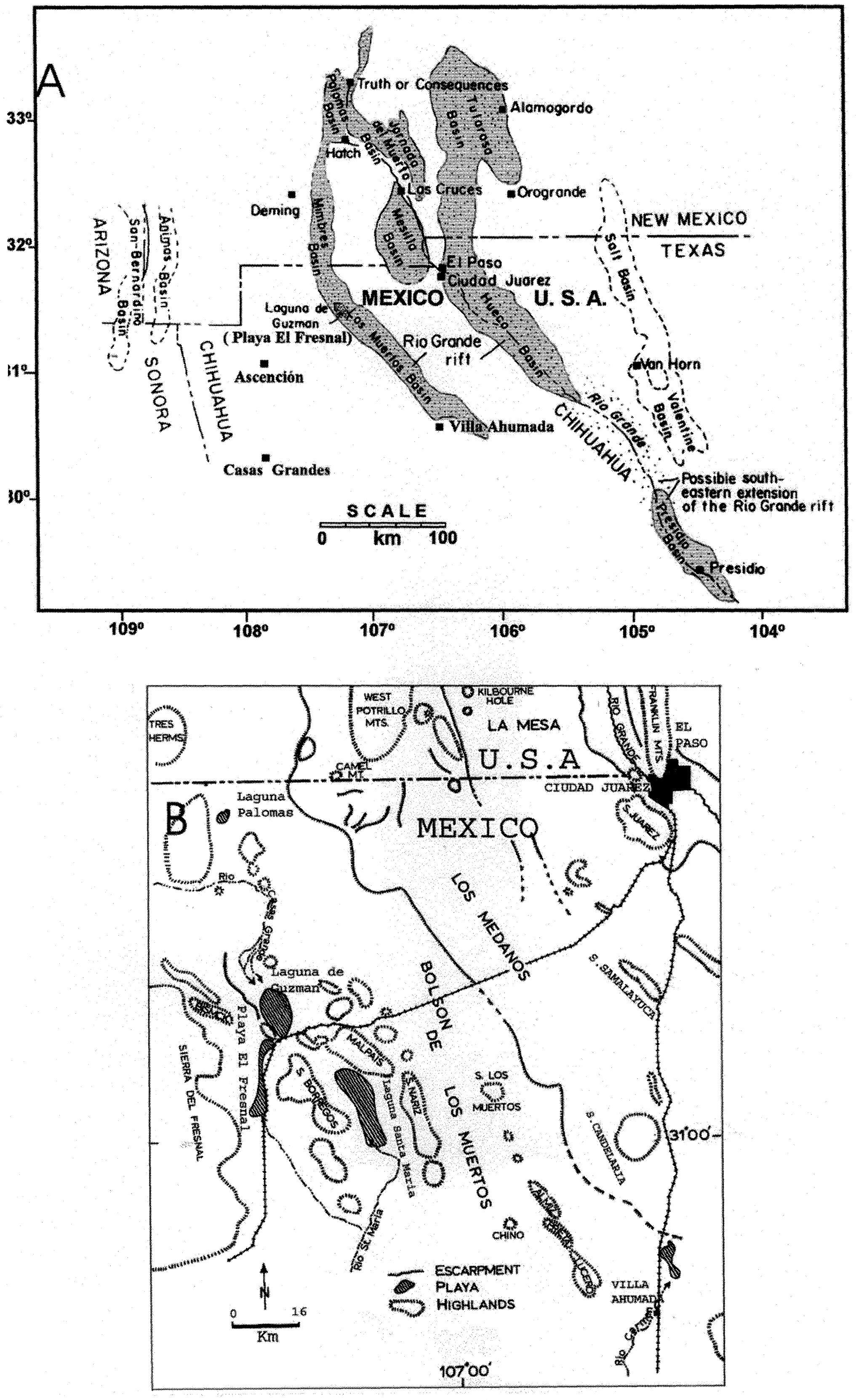

Fig. 2. (A) Bolsons in the southern Río Grande Rift of Texas and New Mexico, United States, and of Chihuahua, Mexico (Map modified from Stuart and Willingham, 1984); (B) Northwestern Chihuahua showing the general area of pluvial Lake Palomas and the playa lakes: Laguna de Guzmán, Playa El Fresnal and Laguna Santa María: (Map modified from Revees, 1969).

12 km long, 10 km wide (Figure 3 A, B) and encompasses approximately 120 km^2 of flat surface at an elevation of 1200 m a s l (Figure 3 C). Playa El Fresnal is bounded to the west by the north-south elongated mountains of the Sierra El Fresnal, in which elevations range from 1200 m to 2100 m within a 9 km horizontal distance, and to the east by the north-south elongated Sierra Los Borregos and Cerro El Venado, in which elevations range from 1200 m to 1600 m within a 12 km horizontal distance (Figure 3 C). These ranges are built of mid and upper Tertiary silicic volcanic sequences and Pliocene/Pleistocene plateau-type basalts (Seager *et al.*, 1984). Active depositional environments include coarse-grained alluvial fans along the basin margins, and axial playa sediments in the basin floor. Late Quaternary basin-bounding fault scarps (Figure 4) along the western and eastern fault zones have significantly affected sedimentation on piedmont fans and have also influenced the development of different types of alluvial fans that occurs along both sides of the surrounding relief, indicating neotectonic activity and climatic fluctuations (Ortega-Ramírez *et al.*, 2001).

At present, sedimentation is occurring in these environments under hot and dry conditions, with annual rainfall averaging 238 mm/year (calculated over a period of 30 years at four stations close to the study area: Ciudad Juárez, Janos, Samalayuca and Ascención), with summer daily high temperatures reaching as high as 44 °C and winter daily low temperatures reaching -18 °C.

In order to establish a reference for characterizing the present arid climate in the playa-lake El Fresnal region, we used the 1970's climatological data from the city of El Paso, Texas (Schmidt, 1986), located near the study area (~ 120 km). These data indicate that 45% of the precipitation in summer is due to the effect of cyclones in the Pacific ocean; the remaining 55% is due to the influence of the Bermuda High in the Gulf of Mexico. To explain the precipitation pattern, Mosiño and García (1974) propose that a pressure trough over the Mexican highlands allows tropical storms from the Gulf of Mexico and/or the Pacific ocean to enter the region. Conversely, pressure ridges could block the easy passage of humid air masses during the summer and cause drought conditions.

In regard to bioclimatology, Playa El Fresnal lies in the northern part of the large continental desert known as the Chihuahuan desert. The vegetation distribution is mainly influenced by available moisture and correlates closely with elevation. In general, vegetation on the basin floor consists of *Distichlis spicata* var *stricta*, *Suaeda palmeri*, *Atriplex canescens* and *Artemisia filifolia*. With increasing elevation, the foothills are covered with Mesquite scrub communities dominated by *Prosopis glandulosa* and *Ephedra trifurca*, *Larrea tridentata* (gobernadora), and *Flourencia cernua* and lesser numbers of *Acacia neovernicosa*, *Fouquieria splendes*, *Koeberlinia spinosa* and *Yucca elata*. Discontinuous areas of *Juniperus* sp. lie between 1800 and 2300 m.

3. GEOLOGICAL STRUCTURE

The Playa El Fresnal is located within a prominent, north-south oriented, half-graben, extensional basin, which is bounded by segmented faults that produce hanging-wall down tilting and footwall uplift. Uplift and subsidence around normal fault zones results in pronounced asymmetry of the basin topography that controls the development of transverse, drainage catchments on footwall and hangingwall blocks. These catchments act as a primary control on the distribution of sedimentary environments and lithofacies, and supplies sediments to fans (Leeder and Jackson, 1993). A further control on drainage development is related to the border fault zones; high-gradient slopes give rise to narrow, linear basins with higher drainage densities (relatively short, small and first order channels), whereas low gradient slopes give rise to broad palmate basins with longer drainages.

In the northern sector of the Playa El Fresnal region, the faults dip eastward, whereas in the south they dip westward. These faults are intersected by a large canyon formed by a synthetic fault that crosses the entire basin in a northeast-southwest direction (sections A-A' and B-B' in Figure 5). The effects of surface tilting on these lateral and axial systems give rise to marked basin-wide variation of facies and thickness. In the northern part of the basin, the transverse fan deposits and the axial through drainage occupy a very narrow (<2 km) belt. Towards the middle, they broaden to > 6 km. To the south, the graben system changes polarity (Bandy *et al.*, 2002). The width of the drainage through diminishes drastically to 1 km, and is oriented northwest southeast (cf. Figure 5). Thus, both the northern and southern areas are similar to the tectono-sedimentary facies model B of Leeder and Gawthorpe (1987), or a continental basin with axial through-drainage; whereas the central part corresponds to facies model A, or a continental basin with interior drainage. The thickness and the chronostratigraphic sequence of the sedimentary axial deposits in the basin are not well understood; however, gravity modeling (Bandy *et al.*, 2002) indicates that the basin consists of two sub-basins. The southern sub-basin contains 800 meters of sediments whereas the northern sub-basin, in which is located the Playa El Fresnal, contains 1500 meters of sediments (Figure 6). These sub-basins are separated by a basement high that is now buried by roughly 500 meters of sediments.

4. GEOMORPHOLOGY OF ALLUVIAL FANS

Considering the differential uplift of the mountain block with respect to the valley, two basic types of alluvial fans in the study area can be considered.

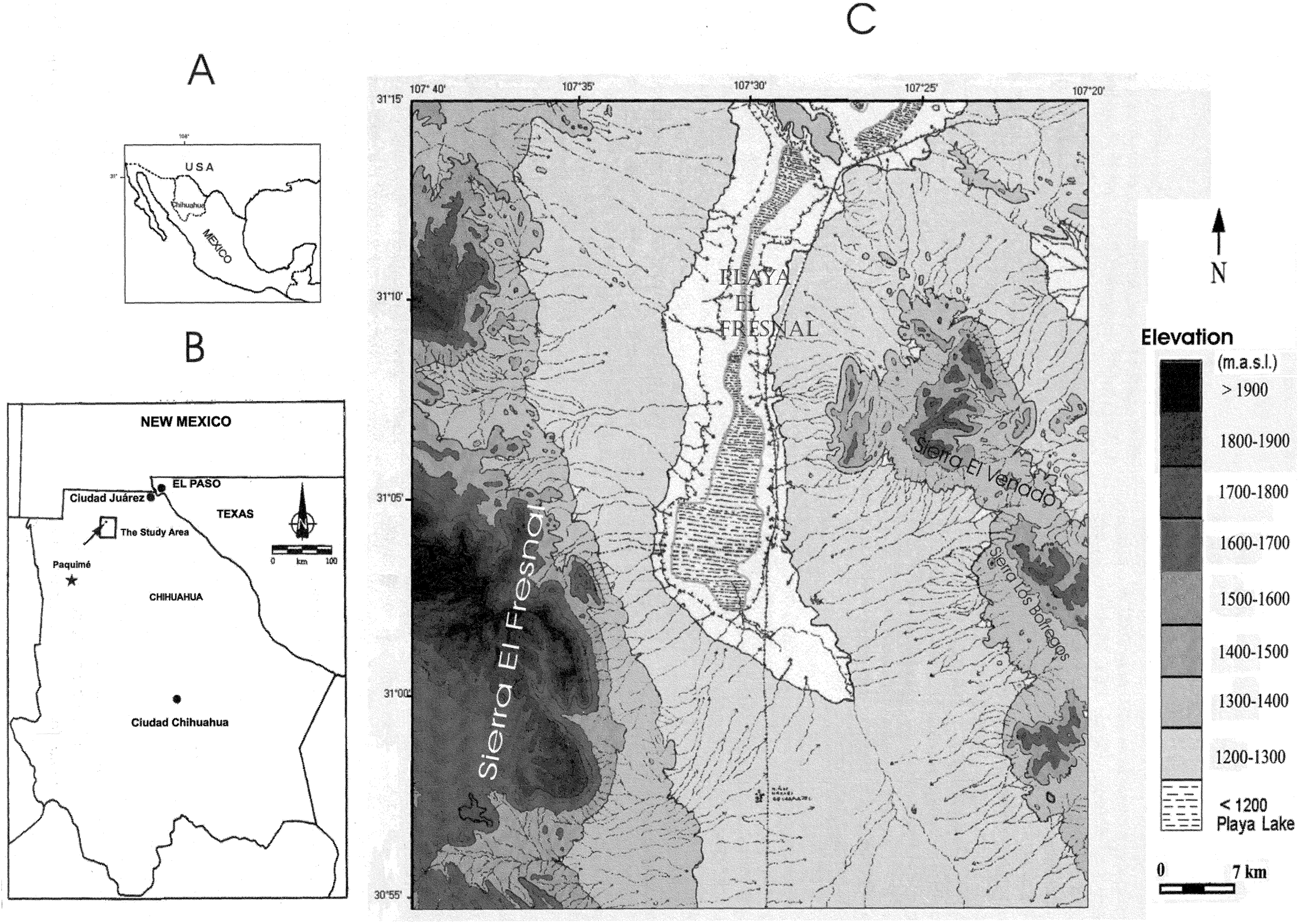

Fig. 3. (A, B) General location map of the El Fresnal basin area in northern Chihuahua, Mexico. (C) Elevation map and location of detailed study area discussed in this paper.

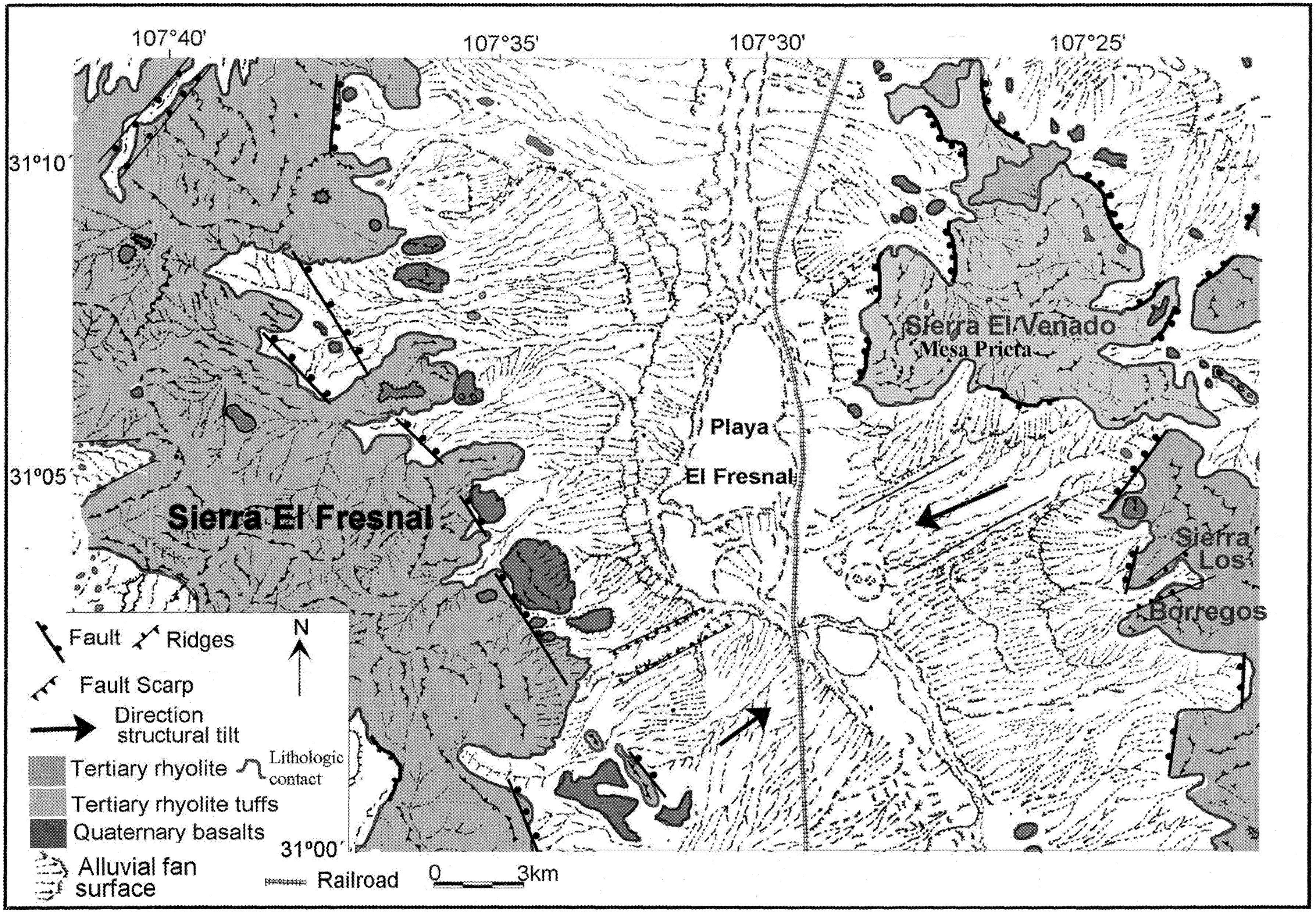

Fig. 4. Generalized geologic and tectonic map of the El Fresnal basin illustrating the sense of regional tilting. Note that north of approximately 31° 03´N the structural tilting is to the west.

The first type of alluvial fan develops where the rate of uplift is greater than the rate of stream channel downcutting. The channel distributaries flow toward the toe-edge and are not able to distribute the sediments from the locus of maximum deposition in the apex region toward the lateral edges. Consequently, the apex experiences the cumulative effect of surplus deposition that results in the steep convexity of the proximal segment; whereas in the distal part, the diverging distributaries move sediment from the axial belt toward the lateral margins over a much wider fan surface thus reducing the difference in elevation. The rate of denudation is slower than the rate of uplift and coarse-grained alluvial fans are formed within, and restricted laterally to, a narrow zone directly adjacent to the uplifted terrane (Bull, 1977; Mack and Seager, 1990).

In the margin of the front range of the Playa El Fresnal, along the offset of the footwall blocks in the northwestern and southeastern side (Figure 5, Section A-A', B-B'), these marginal fans contain talus deposits near the apex and are thus debris fans (Kochel, 1990) (Figure 7A). These fans are fed by generally short, steep, and small drainage basins giving rise to only small (usually between 3 to 5 km wide and in general not more than 5 km in length) alluvial fans. These alluvial fans show approximately three segments which appear as slightly curved lines on the radial profile, the angles of dip are gentle (<5°) and have subdued convex slopes. The segments exhibit uniform slopes and are bounded up-fan and down-fan by breaks in slope, which are roughly concentric with the fanhead (cf. Figure 7 C). They support a large number of the first order streams in a deeply incised parallel network, that, if extended upstream, they would converge on a common point near the fan apex (radial pattern; cf. Figure 4). The fan segments are younger in the upfan direction resulting in deposition adjacent to the mountain front while in the distal front, older surfaces are depositionally inactive and subject to pedogenesis, especially calcretization (Figure 7B). A notable exception is a large alluvial fan located to the northwest side of the basin, which is segmented probably due to en échelon steps in the main fault trace (Machette *et al.*, 1991). These fans can be classified as steep fans with pseudotelescope structure (Blissenbach, 1954), as fan-wrapped type (Hunt and Mabey, 1966), as uncoalesced fans (Blair, 1999a) or as segmented fans (Bull, 1964).

The second type of alluvial fan occurs where the rate of channel downcutting at the mountain front exceeds the rate of uplift of the mountain and the erosion rate eventually surpasses subsidence rates. The low gradients slopes give rise to broad palmate basin with longer drainage channels feeding alluvial fans with limited head-incision and become progressively larger and coalesced. The fan-head becomes entrenched and the locus of deposition moves downslope from the fan apex. Thus, the fan-head area will be removed from active deposition, resulting in a new fan segment with a lesser gradient. The fan segments are younger and gentler in the downfan direction (Hooke, 1972; Bull, 1977; Mack and Seager, 1990). This may also occur where stepped fault offset has caused greater base-level subsidence of the distal fan and development of long incised channels extending from the apex to distal depositional lobes, or by abandonment of the uplifted fan segments as a result of incised-channel downcutting (Blair, 1999b).

In the Playa El Fresnal region, the hanging-wall-sourced bajadas are located in the eastern side between Mesa Prieta and Sierra Los Borregos, and in the southeastern part of the Sierra El Fresnal (cf. Figure 4). The fans are commonly coalesced and extend radially for 6 to 12 km. They are derived from a large elongate catchment with a surface slope that decreases radially from 5° to 1° dip and with subdued concave slopes. Low gradient slopes give rise to a broad palmate basin with dendritic drainage and incised channels, that extends until the head of the distal fan depositional lobe, ~ 8 km below the apex. The fan streams that originate in the proximal and mid-fan areas are of the consequent type or superposed stream and reveal a more regular, concave longitudinal profile. These streams are significantly larger than the footwall drainage streams. The increased sediment flux from these hangingwall basins has formed wide bajadas of large alluvial fans along the base of the ranges. These fans can be classified as superimposed alluvial fans (Blissenbach, 1954), fan-frayed type fans (Hunt and Mabey, 1966), fluvially dominated fans (Blair and McPherson, 1994), non-dissected fans (Blissenbach, 1952) or coalesced alluvial fan (Blair, 1999a).

In addition to the active zones of a terminal fan system there is also the region into which the system drains, this area is a playa lake. The basinal zone only receives very fine-grained sediment after a large flood, and distributary channels extend into this zone only during extreme flood events. The basinal zone is characterized by sand sheet-deposits associated with evaporitic and lacustrine deposits.

Figure 5 provides an example of the different morphologies. It also illustrates the distribution of alluvial fan units and the relation between tectonic features and sedimentary deposits.

4.1. Sedimentary facies and distribution

Fan facies were studied along a full longitudinal transect, roughly along cross section A-A' (Figure 5), following an incised channel and in gully-side exposures of the distal depositional lobe. The geomorphology and the soil data (Btk horizonts) from both the older proximal and distal deposits, and the distal-lobe deposits along both sides

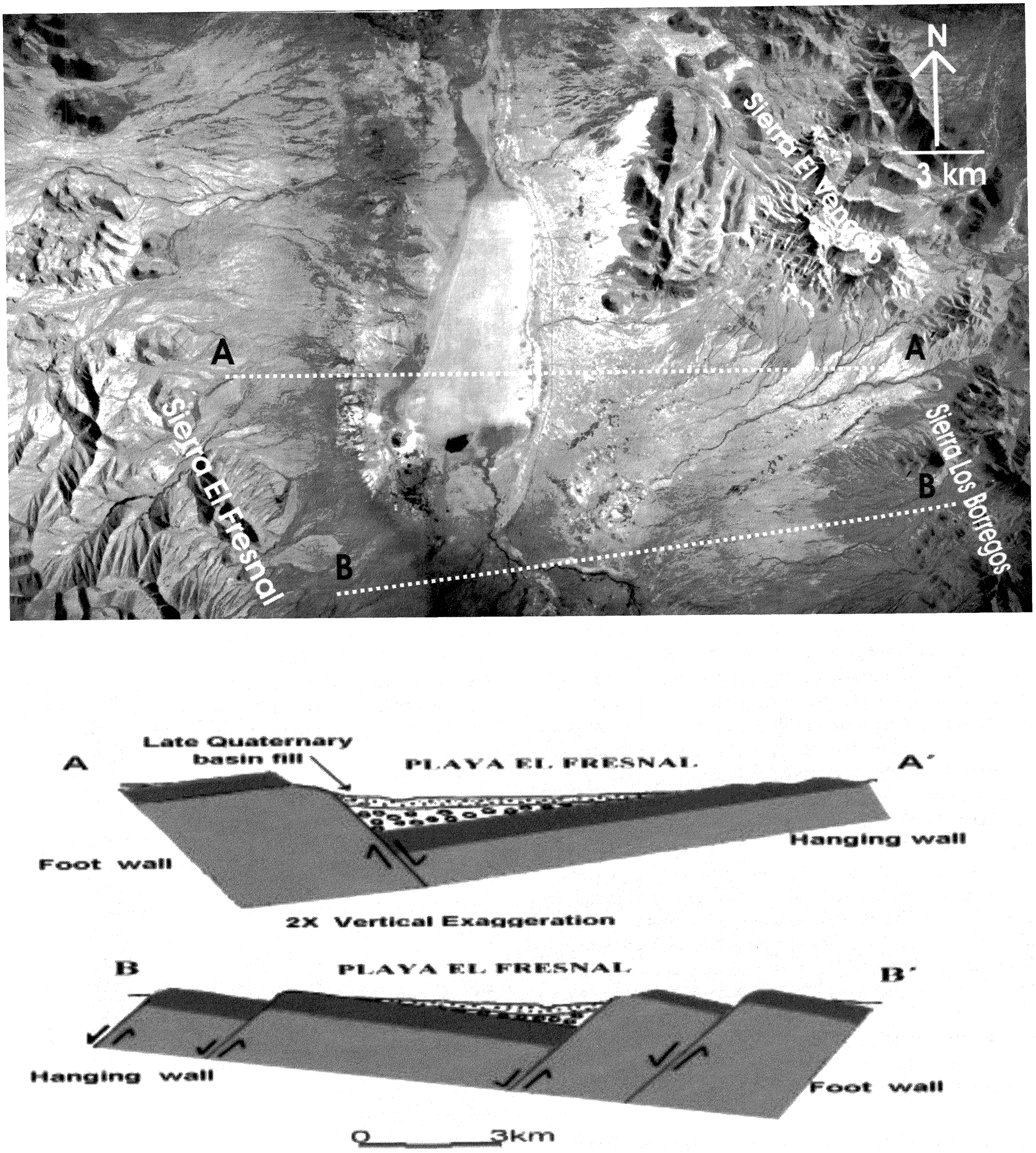

Fig. 5. Airphoto view of alluvial fans and geomorphologic features of the El Fresnal Playa Lake. Dotted lines A-A´and B-B´ are the traces of the cross-sections shown in figure. Note that the foot-wall catchments are shorter and steeper than those in the hanging-wall.

of the valley, indicate that the exposures collectively record the Late Quaternary stratigraphy. Thus these exposures provide a reasonable representation of the short-term sedimentological processes that have built the fans. Regardless of age, the exposures consist of four facies: 1) non-stratified colluvial deposits (debris-fans), 2) imbricated and clast-supported, granular pebble-gravel with muddy sand-supported matrix, 3) winnowed muddy silty-clayey deposits and, 4) medium to fine sands. A complete review of these facies can be found in Ortega-Ramírez *et al.* (2001).

5. MORPHOSTRATIGRAPHY OF ALLUVIAL DEPOSITS

In the footwall slopes the fans exhibit a characteristic fan shape. The fans are segmented with younger units inset into older units in proximal areas, but generally overlapping older units in distal areas. In contrast, in the hanging-wall slopes the alluvial fans coalesced to form an alluvial slope along the distal margins of the fans.

The fans are composed, from oldest to younger, of three stratigraphic units: I, II and III. Each unit has a distinct combination of spatial, morphologic, and pedologic characteristics. The older surface informally referred to as Unit I, is preserved in the proximal areas of the gentler hangingwall slope. In the footwall, Unit I is generally preserved on the distal fan areas and exhibits a weakly convex-concave longitudinal profile with incision in the proximal areas and rapid aggradation on the depositional lobes. Where associated with faulting, Unit I is generally preserved on the upthrown block. The drainage pattern on the fan surface is dendritic on the hanging-wall slopes and parallel at the footwalls. Calcium carbonate clasts scattered on the present surface give evidence of the destruction of a petrocalcic horizon in the distal fan of the footwall (cf. Figure 8 A) and a buried Btk horizon in the proximal area of the hangingwall slope (Figure 8 B). Unit I is overlain by the intermediate-age, alluvial fan, deposits which comprise Unit II. These deposits have subdued convex slopes on the footwall slope and are coalescent in the hangingwall slope. In the former, they are incised, and in the later, they still retain much of their original topography. The distributaries are mostly dendritic with abundant pebble-gravel lag deposits and buried soils (Bt horizon) (Figure 8 C). Unit III, the youngest alluvial-fan surface, is inset into

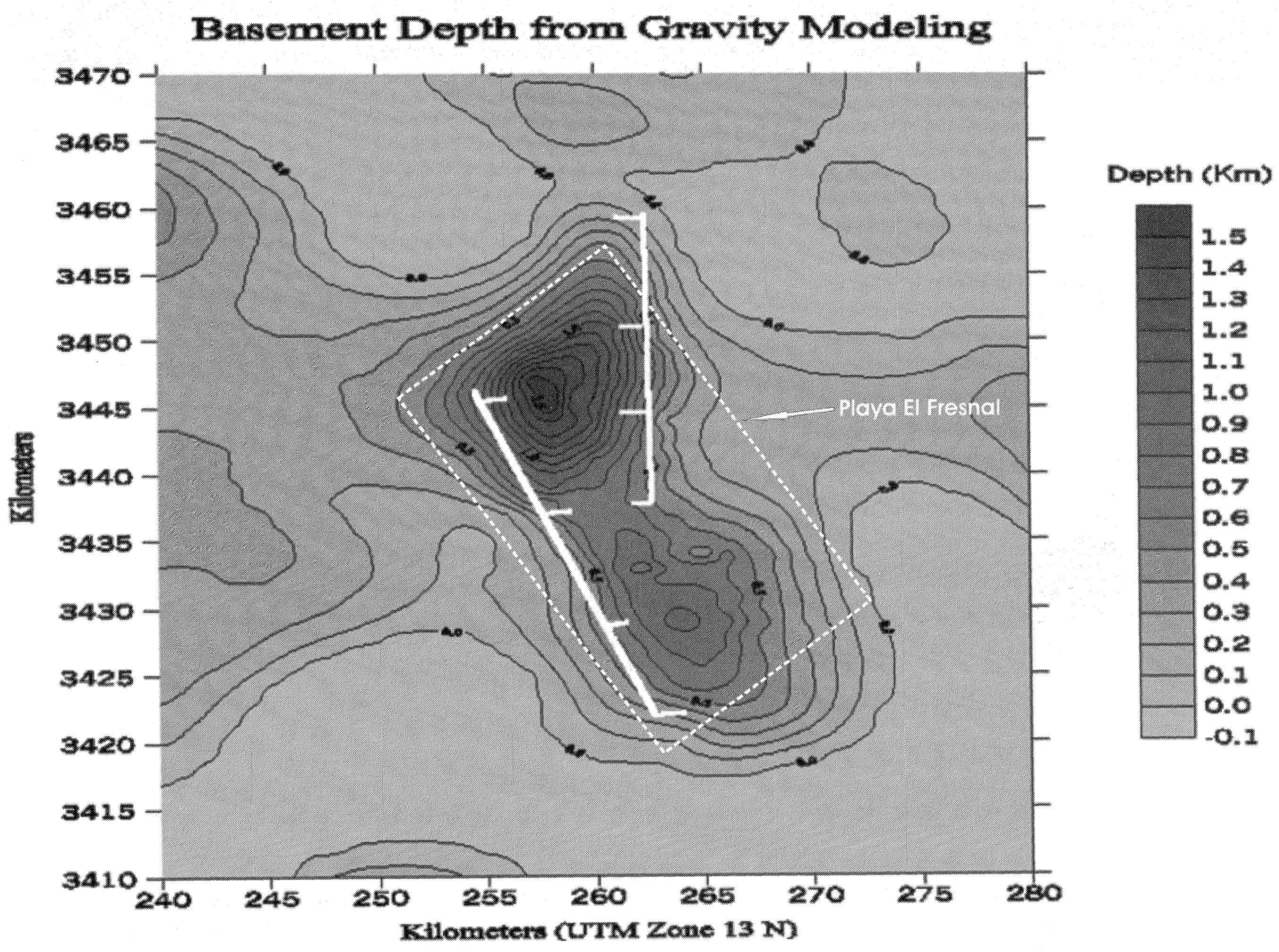

Fig. 6. Depth to basement calculated from gravity data. Coordinates are UTM zone 13N.

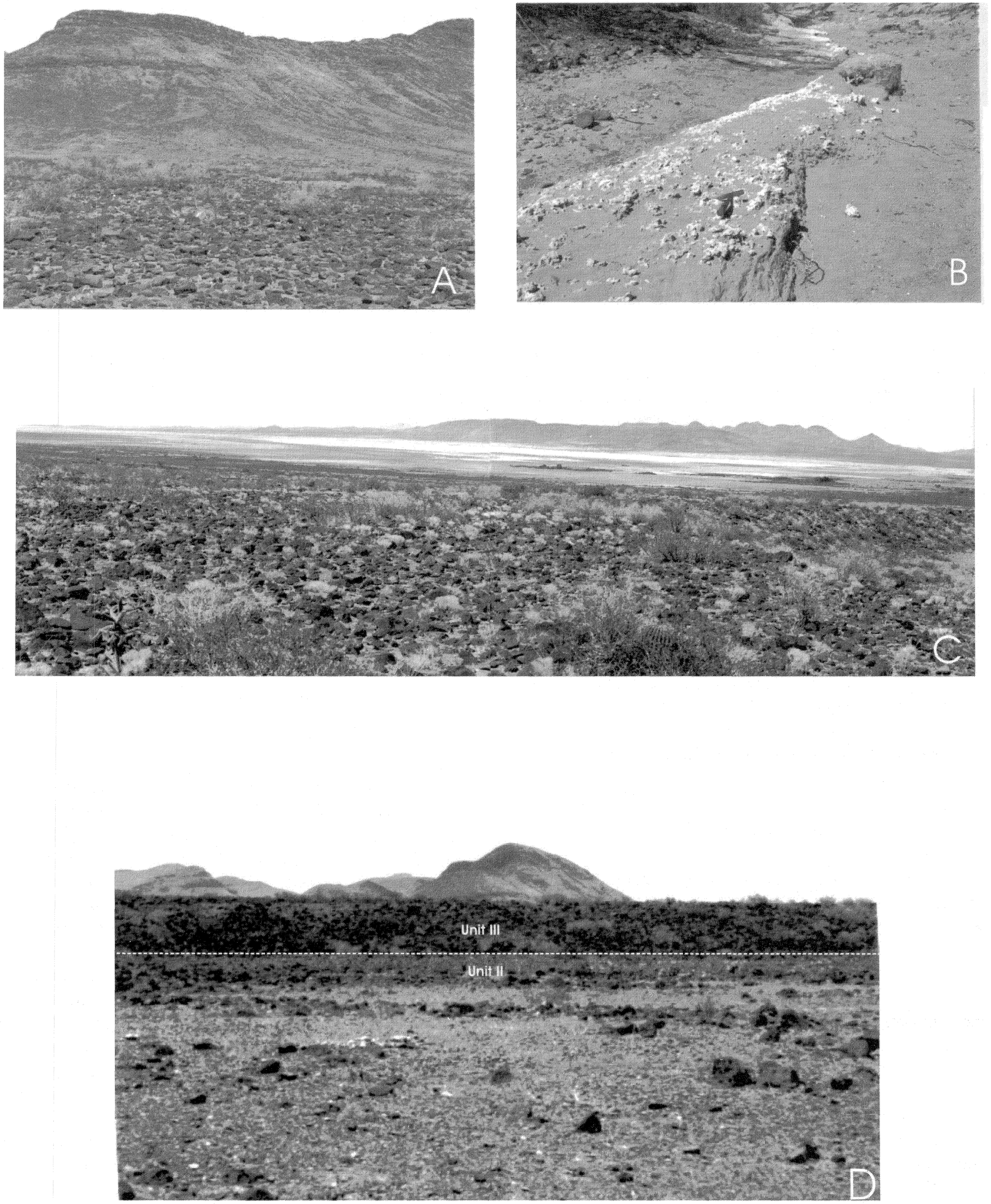

Fig. 7. (A) Close-up of the fan apex, debris fan. (B) Clast of petrocalcic Bk horizon exhumed by erosion. Distal part of the oldest alluvial fan surface (I) at the northeastern foot wall slope; hammer is 28 cm long. (C) Photograph looking east toward the plain. Note the convexity of the middle fan segment corresponding to the foot-wall slope. (D) Inset relation between the surfaces of Unit II and Unit III ranges from 5-10 m.

Unit II in the proximal area of the fan on the footwall slope and in distal areas of the hangingwall slope. Where the inset relation exists, the relief between the surfaces of Unit II and Unit III ranges from 5-10 m (Figure 7D). The deposits which collectively comprise Unit III, are similar to those referred to as coalescent colluvial fans (Blikra and Nemec, 1998) or debris-fan deposits. They typically have the form of relatively steep and short fans or 'cones' dominated by debris flows and, to a lesser degree, by rockfall deposits (cf. Figure 8C). These surfaces in the footwall slope are steeper and occur where depositional processes are associated with predominantly coarse sediments and a permeable surface (cf. Figure 7A), and upon which the distributaries consist of a relatively closely spaced system of parallel channels. In contrast, in the hanging wall slope, the unit is represented by a gentler surface covered by coppice dunes and contains a longer drainage net (cf. Figure 4). In both cases, alluvial-fan deposits lack soil-profile development because of their youth and aggrading conditions. Two other distinct geomorphic surfaces are observed, herein called surfaces IV and V. Surface IV corresponds to older distal fronts of alluvial fans at the eastern margin or hanging-wall slope, indicating that the surface is no longer active (Figure 8D); whereas in the footwall, this unit is represented by incised channels and depositional lobes (Figure 8E). Lastly, surface V (the playa floor or depocenter) is characterized by fine silty-clayey sediments of aeolian origin (loess-like) and silty-clayey flood plain deposits, associated with sulfates found in disseminated form or as small lenses and laminations. These properties, according to Motts (1970), place the area in the category of fine grain playas (Figure 8F). Surface V is probably as young as the aeolian sand sheet, forming the coppice dunes at the distal fans of the hanging wall slope.

6. CORRELATION

The morphostratigraphic units are not of uniform thickness because aggradation may be occurring on one part of a fan while another part is being eroded or is in a steady state. For instance, fans on the footwall on the northwest and southeastern sides of the basin have been tilted and incised in the head, while fans on the hanging walls located on the eastern and southwestern side show recent deposition concentrated near the toe in a down-fan thinning wedge. Thus, the footwall slope in the western and southeastern sides (faults-offsets of Sierra El Fresnal and Sierra Los Borregos, respectively) are covered by segmented fans where breaks in slope coincide with the wedge-shaped edges of units I, II and III. They have steeper gradients (<5°) and are concave upward in profile, suggesting that the relief between mountains and alluvial fans is the result of the subtle control exerted by periodic tilting and/or climatic change.

The lack of radiometric data from the units makes it difficult to constrain their ages; however the degree of soil development (horizon Btk) in Unit I and II deposits as well as the morphostratigraphic position indicates that they are time stratigraphic correlated at both sides of the footwall margins. In contrast, hanging wall-sourced fans have a gentle dip that decreases distally approximately from 5 ° to 1°. They have a subdued concave slope and incised channels spanning 8-12 km from the fan apex to the depositional lobe, which is less active, non-dissected and covered in the distal section by aeolian sand-sheet forming coppice dunes. Morphostratigraphic units are not completely discernible and only older exposures close to the apex contain buried soil with a Bt/Btk horizon (5YR 6/4 and 5YR 4/8) corresponding probably to the oldest segment (I). This suggests that the tilting has steepened the fans and the subsequent runoff has incised the fanhead, thus tending to regrade the fan to the equilibrium slope. It seems possible to propose a correlation between the coalesced alluvial fans from the eastern and southwestern sides of the basin corresponding to the hanging wall slopes. Figure 9 schematically summarizes our interpretation and correlation.

7. DISCUSSION

Active tectonism is of first-order importance in generating sources of, and depositories for, sediment in continental basins where subsidence is required for the accumulation of thick clastic successions; however, other factors such as lithology and geomorphology of the upland source area vary along the periphery of the basins. Although thresholds for climate influences on alluvial sedimentation are not well known, we assume that climate was uniform within the basin during any one point in time; therefore, a decrease in effective precipitation initiates time-transgressive changes in plant communities and diminishes hill-slope vegetation densities that increase sediment yields and runoff (Bull and Schick, 1979; Smith, 1994). The impact of this vegetation change can be so profound that it might control alluvial-fan sedimentation process regardless of regional variation in tectonic activity (Bull, 1991; Lusting, 1965; Ritter *et al.*, 1995). For example, the stratigraphic investigation of Reheis *et al.* (1996) on the Leidy Creek alluvial fan in the Fishlake Valley of Nevada and California indicates diminished fan deposition and development of thick soils during the late Pleistocene glacial maximum. At this time fan surfaces were essentially bypassed as fan channels incised in response to reduced sediment supply and increased runoff (Leeder *et al.*, 1998). In the Holocene, Ortega-Ramírez *et al.* (1998) reported for northern Mexico higher temperatures, aridity and dominance of summer convective precipitation has caused tree lines to rise substantially and the incidence of debris-flow deposition from poorly vegetated catchment slopes onto alluvial fans to increase. The same pattern has been identified elsewhere in the American Southwest (e.g. Bull and Schick, 1979; Wells *et al.*, 1987; Bull, 1991; Leedder *et al.*, 1998).

Because thresholds for sediment supply are sensitive to changes in vegetation density and runoff-infiltration regimes, we suggest as a plausible explanation that the different alluvial fans recorded in the Playa El Fresnal region are related to periods of climatic variation during the late Quaternary, because climate change directly affects transport efficiency and thus slopes. Although some of the conclusions presented below are admittedly conjectural, they are consistent with one another and form the basis for the interpretation of alluvial fan response to changing climate.

For purposes of the present study, the most significant effects of late Quaternary climatic change are the lake-level fluctuations in the Babícora basin (Ortega-Ramírez *et al.*, 1998). This is a semidesert paleolake located about 120 km southwest of the study area which contains evidence that during the late Glacial (>11 ka B.P) cold temperatures and increased effective moisture prevailed, resulting in high lake stands synchronous with the pluvial lakes in the southwestern United States (Smith and Street-Perrott, 1983; Allen and Anderson, 1993). During the late Glacial time, fan deposition ceased or fans and slopes were stable, soils formed, perennial streams probably flowed across the basin floor and the vegetation cover was abundant inhibiting fan aggradation (Reheis *et al.*, 1996). This is in accord with Denny's model (1967) which links aggradation with arid phases and entrenchment with humid phases, and is contrary to the climate-driven models that propose epochs of fan aggradation with humid periods (increased rainfall) and epochs of fanhead incision with drier intervals (Lusting, 1965; Smith, 1994; Ritter *et al.*, 1995). We do not have direct evidence, but it seems possible that the thickest basin fill was deposited during this late Glacial time (>11 ky B. P.) under humid conditions.

Investigations of Quaternary paleoclimatic changes conducted in northern Mexico and the American Southwest demonstrate a remarkable temporal incidence of relatively dry and warm climatic conditions at about 11 ka B. P. (Pleistocene/Holocene boundary), as is registered in the sedimentological records from the Laguna Babícora (Ortega-Ramírez *et al.*, 1998), the drying of pluvial lakes in southeastern California (Smith, 1968), the Great Basin (Benson *et al.*, 1990), at the Fish Lake Valley in Nevada and California (Reheis *et al.*, 1996); and is represented by coarse grained sediment load deposits, in the Sonoran Biogeographic Province of Arizona (Waters and Ravesloot, 2000) and northern Chihuahua Mexico (Nordt, 2003).

This change from relatively wet to dry conditions, caused soil moisture and vegetation cover to decrease, which resulted in an increase in sediment yield, flash flood and sediment flux. This rapid sedimentological change implies that either the regional climate was changing rapidly during this time or a climatically triggered geomorphic threshold occurred. In either case, the onset of fan aggradation probably reflects a change from stable vegetated slopes to eroding, poorly vegetated slopes and intermittent streams characterized by flash floods and debris flows. In the Playa El Fresnal this resulted in filling of the valley and fan deposition in the basin. Thus, surface I was probably deposited at this time.

During the early Holocene (11-8.9 ka), the temperature continued to rise, but the climate was still cooler and wetter than today, particularly between ca 11 to 10 ka. Lake levels in Laguna Babícora in northern Mexico (Ortega-Ramírez *et al.*, 1998), Lake Estancia in New Mexico (Allen and Anderson, 2000; Anderson *et al.*, 2002) and Lake Lahontan in Nevada (Benson *et al.*, 1992; Currey *et al.*, 2001) all increased during this period. The moisture increase was probably mainly from increased summer precipitation (monsoon type) related to an increase in the solar radiation (COHMAP, 1988). Alternatively, this humid condition could be related to the climatic anomaly of the Younger Dryas, when the atmospheric conditions were similar to the prevailing winter rainfall and cooler temperatures of the Late Pleistocene (Ortega Ramírez *et al.*, 1998). We deduce that this climatic change from arid to humid may have increased the vegetation cover, which would have hindered erosion resulting in soil profile development. The buried horizon Btk in the proximal area of the hanging wall (cf. Figure 8 B) and the carbonate clasts scattered on the present surface in the distal fan of the northwestern footwall (cf. Figure 8 A) may have formed during this period. Subsequent to ca 9000 yr B.P., the hydrologic regime on Laguna Babicora, based on inferences drawn from the geochemical and sedimentological data, imply a time-transgressive climate change characterized by a decrease of the effective moisture, however, this was greater than during the rest of the Holocene (Ortega-Ramírez *et al.*, 1998). Following the model of Bull and Schick (1979) and Bull (1991), the climate change from relatively wet to dry conditions causes soil moisture and vegetation cover to decrease and consequently an increase in sediment yield, flash floods and sediment flux. We suggest that the surface II was deposited at this time.

The sedimentary environments in Laguna Babícora corresponding to the middle Holocene (8.9-4 ka) are bogs associated with aeolian deposits (loess). An increase in frequency of arroyo formation and fine-grained valley filling is observed in the Casas Grandes and San Pedro River basin in the northern Chihuahua (Nordt, 2003), which indicates that the effective moisture decreased. This is interpreted as the result of increased evaporation rates associated with increased temperature. The warmest and driest period of the mid-Holocene reached a maximum around 6 ka BP (Ortega-Ramírez *et al.*, 1998). These climatic conditions are also reported in the paleolacustrine data for the American Southwest (e.g. Markgraf *et al.*, 1984; Weng and Jackson, 1999)

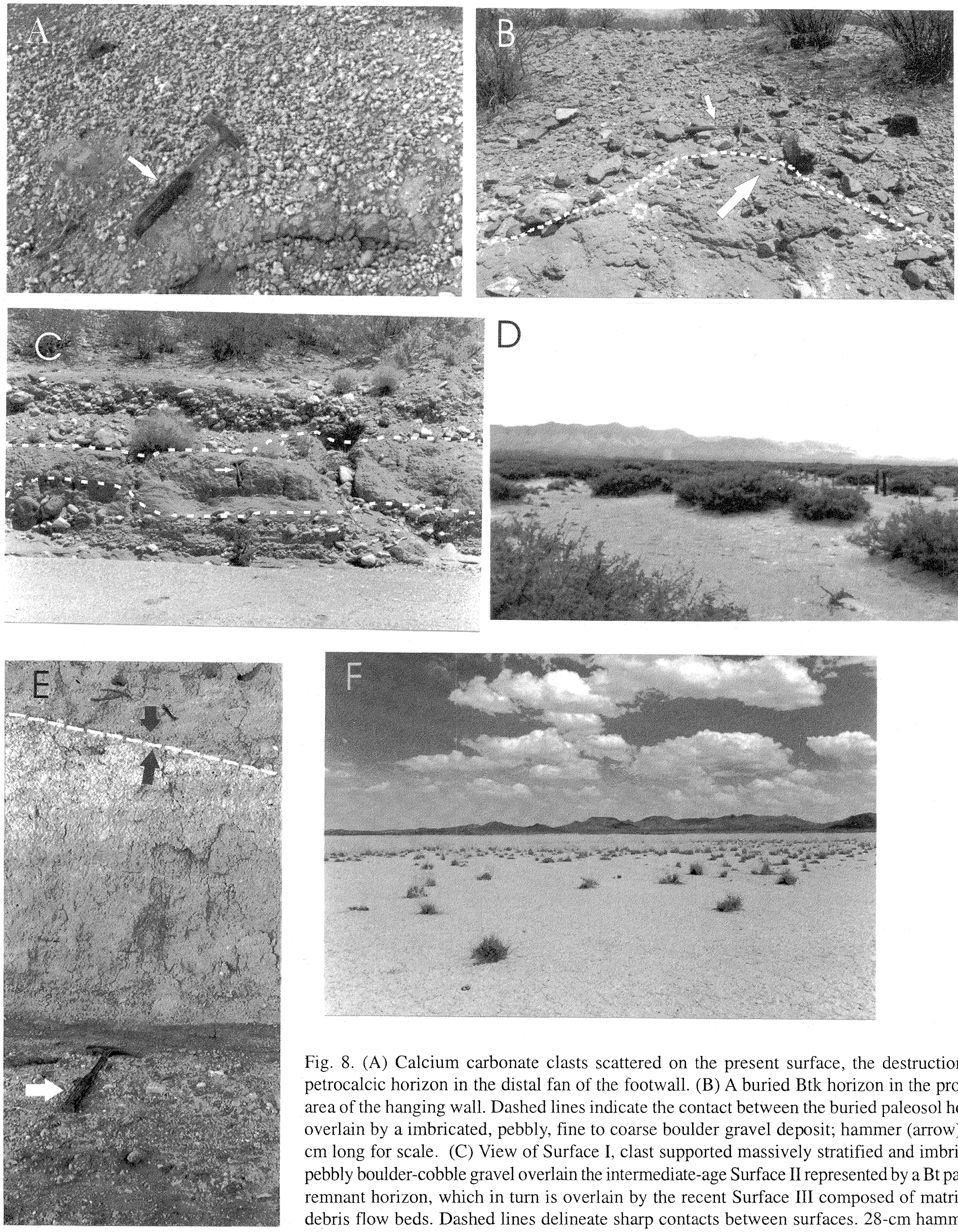

Fig. 8. (A) Calcium carbonate clasts scattered on the present surface, the destruction of a petrocalcic horizon in the distal fan of the footwall. (B) A buried Btk horizon in the proximal area of the hanging wall. Dashed lines indicate the contact between the buried paleosol horizon overlain by a imbricated, pebbly, fine to coarse boulder gravel deposit; hammer (arrow) is 28 cm long for scale. (C) View of Surface I, clast supported massively stratified and imbricated, pebbly boulder-cobble gravel overlain the intermediate-age Surface II represented by a Bt paleosol remnant horizon, which in turn is overlain by the recent Surface III composed of matrix-rich debris flow beds. Dashed lines delineate sharp contacts between surfaces. 28-cm hammer for scale (arrow). (D) Aeolian sand deposits which form coppice dunes overlaying ancient distal fronts of alluvial fans at the eastern margin, indicating that Surface IV is no longer active. (E) Massive structureless deposits of the distal transverse fans (lobes), that were probably deposited by hyperconcentrated flood flows with some eolian contribution. Note an erosional contact (arrows) between two surges. Hammer 28 cm for scale. (F) Surface V, the plain or depocenter, is characterized by fine, silty-clayey sediments of aeolian origin (loess) and silty-clayey flood plain deposits, associated with sulfates found in disseminated form.

and are supported by geomorphological, paleontological and archaeological data in the Southern High Plains in the northwestern Texas (Hollyday, 1989). Decrease in effective precipitation initiated time-transgressive changes in plant communities and diminished hill-slope vegetation that increased both sediment yield and runoff. The impact of this climate change was so profound that it controlled alluvial-fan sedimentation processes, valley aggradation and deflation processes. Field observations indicate that debris flood and debris fan events of the surface III could be correlated with this period.

In the late Holocene (4 ka to present) in the Laguna Babícora, marsh and bog environments coexisted, associated with debris-flow deposits, Bt paleosol horizons, and erosion surfaces. These indicate minor humid fluctuation. Several observations support such characteristics of the paleoclimatic conditions, for example a 10 m deep lake probably developed in Death Valley sometime between 4000 and 2000 yr B. P. (Enzel and Wells, 1997), a lacustrine event in the Wilcox Playa in southern Arizona sometime around 4000 to 3000 yr B.P (Waters, 1989), and a brief period of fresh water in the San Joaquín marsh in southern California (Davis, 1992). Evidences for such paleoclimatic variation in the American Southwest have been also related to strong El Niño events (Ely *et al.*, 1993). During this period, the footwall fans in the middle-central western side of the Playa El Fresnal region became incised and active depositional lobes fed by the incised channels were formed (surfaces IV). In the southeastern side, the fans became partially dissected by rills and gullies. At this time, in the hanging-wall fans, the incised channels terminated at the head of the distal-fan depositional lobe, which are presently overlain by aeolian deposits forming coppice dunes (cf. Figure 8D). The later represent the arid condition that presently characterizes the region.

7.1 Paleoclimatic interpretation of the alluvial fans sequence

Several reconstructions of late Quaternary temperature and precipitation have been proposed for the American Southwest based on (1) climatic modeling (Kutzbach, 1983; Kutzbach and Guetter, 1986; COHMAP Members, 1988), (2) paleovegetation reconstructions using pollen from sediments (Martin, 1963; Mehringer *et al.*, 1967) and plant macrofossils from Neotoma middens (Spaulding and Graumlich, 1986; Spaulding *et al.*, 1983; Van Devender, 1987), and (3) periods of increased effective moisture corresponding to high lake stands and periods of normal or decreased effective moisture corresponding to absence of high lake stands and playa conditions or marsh environments (e.g. Waters, 1989; Ortega-Ramírez *et al.*, 1998). These studies suggest that prior to 12 000 yr B.P., when the ice sheets covered much of the North American continent, the Pacific westerlies and their associated winter storm tracks were displaced southward into the American deserts. As a consequence, cooler temperatures, reduced evaporation rates, and increased winter precipitation prevailed in the American Southwest. During this period, monsoonal circulation patterns were suppressed and summer precipitation was minimal (Waters, 1989). Spaulding and Graumlich (1986) suggest that annual precipitation in the Sonoran desert may have been nearly double today's amount. These pluvial conditions correlate well with the occurrence and maintenance of the high stand of lakes in the arid region of northern Mexico.

COHMAP Members (1988) and Spaulding and Graumlich (1986) have suggested that during the Early Holocene (11-8.9 ka B.P) with the rapid disintegration of the North American ice sheets, the modern interglacial climatic regime developed, characterized by a meridional circulation pattern (Waters, 1989). During this period, summer temperatures rose sharply with increasing summer insolation and winter precipitation was reduced from its late Pleistocene high, but was still greater than present day (Van Devender, 1987) because the Laurentide ice sheet was still large enough to influence air circulation patterns (COHMAP, 1988; Kutzbach *et al.*, 1993), although it was melting rapidly. The westerlies were still south of their present position bringing larger amounts of winter precipitation to northwestern Mexico than today (Ortega-Ramírez *et al.*, 1998). Meanwhile, higher summer insolation enhanced the southwest monsoon (COHMAP, 1988), which brought more summer moisture from the Gulf of Mexico and the eastern Pacific ocean. Both winter and summer precipitation were enhanced and may have come from intense rainfall associated with large summer/early fall tropical storms that originated in the eastern North Pacific and tracked into the western United States. A lacustrine record of these events is preserved in the Babícora region of northern Mexico (Ortega-Ramírez *et al.*, 1998), Lake Cochise of southeastern Arizona (Waters, 1989) and even in the Sonoran desert (Van Devender, 1987). By the end of this period, fan deposition was probably triggered by a change from relatively moist to arid conditions.

In the middle Holocene (8.9 to 4 ka B.P.) most of the lakes of the American Southwest, as well as in northern Mexico, receded from their high stands and desiccated (Markgraf *et al.*, 1984; Spaulding and Graumlich, 1986; Oviatt, 1988; Ortega-Ramírez *et al.*, 1998). With the decline of summer precipitation and the onset of the Altithermal, a period of aridity and drought lasting from approximately 7000 to 5000 yr B. P., centered at about 6000 yr B. P. prevailed (Ortega-Ramírez *et al.*, 1998). During this period, deflation processes were more extensive and temperatures were warmer than today's conditions, which produced pulses of alluvial and aeolian deposition. The monsoon was probably stronger than today and summer precipitation may have been also higher. However, high temperatures resulted in higher evaporation. Moreover, the Westerlies probably moved far-

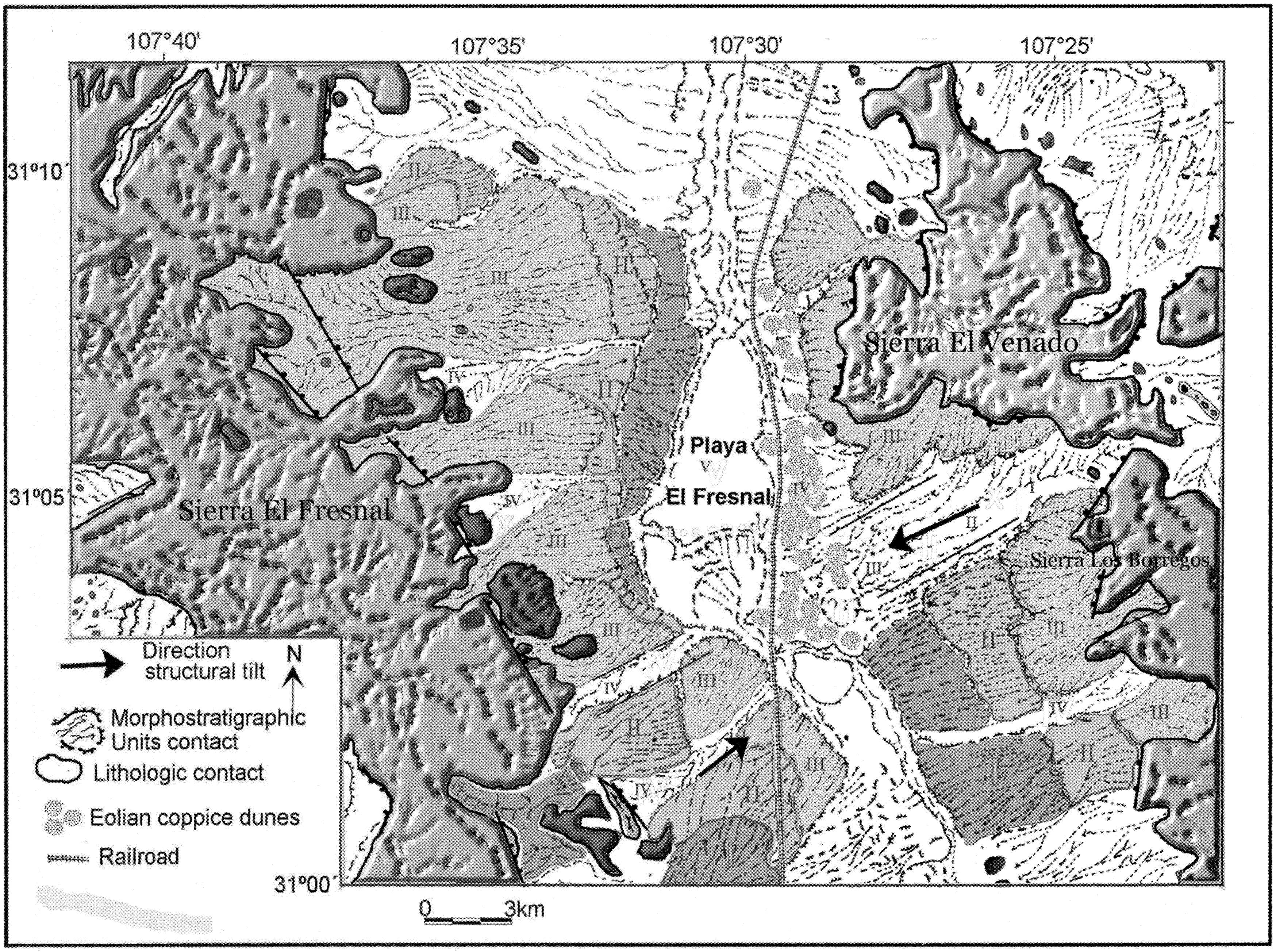

Fig. 9. General geomorphic map of the Playa El Fresnal region illustrating the alluvial fans which are differentiated by numbers.

ther north, so winter precipitation might have declined further.

During the late Holocene (ca 4 ka BP to the present), summer insolation and the intensity of the summer monsoon decreased to near modern levels (Street-Perrott and Perrott, 1993); however, several recent studies document the occurrence of climatic change in this period, which is referred to as the ´Neoglacial Interval´. These studies indicate increased effective moisture beginning between 2000 and 3000 yr B.P. (McFadden and McAuliffe, 1997) as well as wetter and stormier climatic conditions in the southwestern United States at 4000-3000 yr B.P. (Enzel and Wells, 1997). Both imply a change in the main features of the atmospheric circulation patterns. These patterns had to increase the moisture transported into the region and produce heavy precipitation compared to the present, triggering heavy paleofloods of rivers in the American Southwest (Ely *et al.*, 1993). This can be interpreted as the result of a southerly movement of the westerlies in winter after the mid-Holocene period (Enzel and Wells, 1997), which in turn may have brought more winter precipitation and decreased temperatures, resulting in more effective moisture, particularly in the highest elevations. In the study region this is evidenced by the juniper communities, which survive sparsely up in the western range. Figure 10 schematically summarizes our paleoclimatic interpretation related with the effective moisture variation from the Babícora basin.

8. CONCLUSIONS

(1) Tectonism is considered a first-order control on the creation of accommodation space and energy for the fan system. The tectonic process produced normal faulting. These faults played an important role in the initiation of erosion in the source area, fan formation, fan-head entrenchment, the evolution of drainage basin following uplift, and also the segmentation of the fans. Segmentation of fans in the west central segment is attributed to eastward tilting of El Fresnal Range, whereas segmentation in the southeastern area is attributed to westward tilting. On both fans the youngest segments are generally at the head, and steeper slopes of these segments are attributed to an increase in sediment concentration in runoff reaching the fans. Moreover, in the eastern and southwestern sectors, extension of the alluvial fans is very much longer than that to the northwestern and southeastern areas where several generations of fans can be observed. The Playa El Fresnal region is therefore a double half-graben system.

(2) The role of climate in the formation of alluvial fan is considered as a function of the paleoclimatic history of the landform, under the assumption that climatic change has induced widespread changes in mass availability and mass transfer process, characterized by synchronous periods of aggradation and entrenchment for all fans. Thus, fans were formed by rapid deposition, probably triggered by a change from relatively moist to arid conditions. This

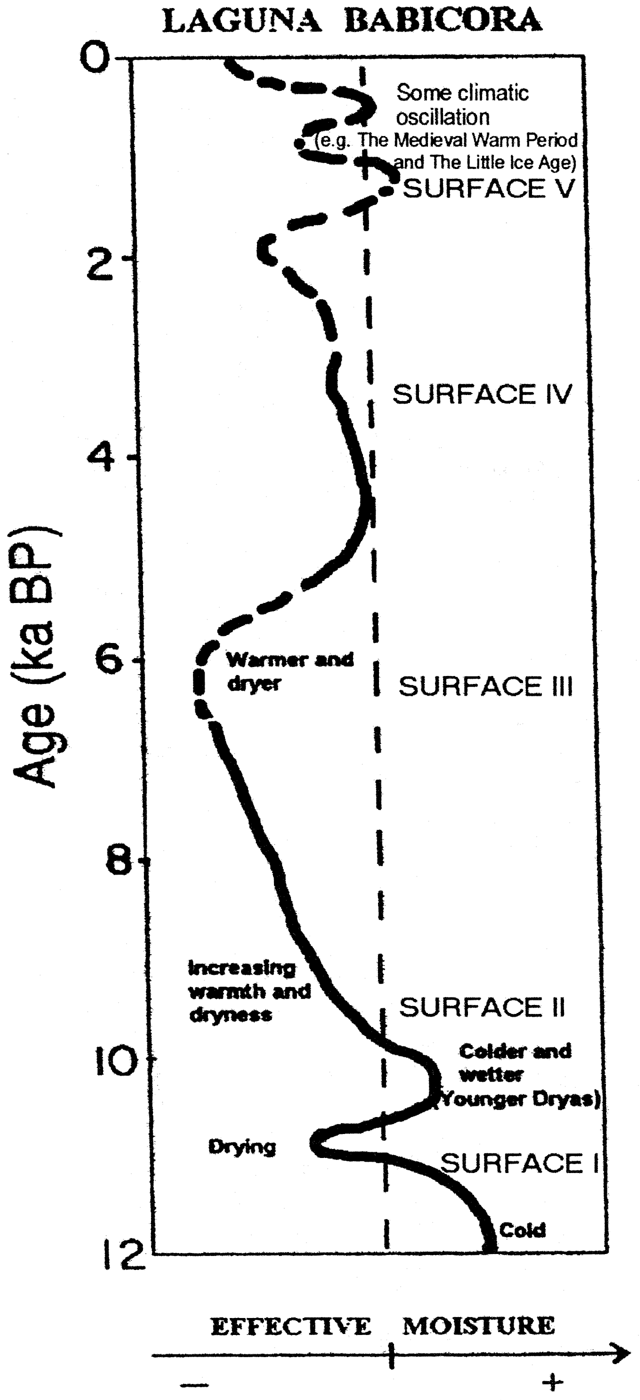

Fig. 10. Paleoclimatic correlation between the alluvial fan surfaces studied in this work, and the general effective moisture curve established for the Laguna de Babícora from the Late Wiconsinian to late Holocene. The dashed extension of the curve represents interpolated data from previous studies (Ortega-Ramírez *et al.*, 1998, 2000).

change produced a decrease in vegetation cover and an increase in flash floods and sediment yield that resulted in filling of the valley within the range and fan deposition in the basin. Thus, it seems probable that these processes were triggered by either an increase in storm frequency or an increase in the intensity of total precipitation.

(3) Despite the lack of absolute radiometric data, our results concerning the stratigraphic relationship, development of soil profiles and morphology of fan surfaces, indicate that alluvial successions provide an important proxy record of regional Quaternary paleoclimatic changes and evidence the asymmetric uplift at several localities. Differences in elevation and fan development are in accord with these suggestions.

(4) Lastly, we conclude that transverse alluvial-fan deposits in the half-grabens reflect both climatic influences and the effect of fault development. Thus, detailed field mapping, absolute-age data, and paleoclimatic studies are all necessary to determine the relative importance of these controls. Future investigations need to be conducted to determine similarities or dissimilarities with the fossil curves for the North-West and South-West moisture. Systematic sampling and detailed sedimentological analysis of the various superficial formations need to be carried out to identify depositional environments and fluvial dynamics, desert pavement, desert varnish, soil-profile development characteristics particularly the stage of development of the B horizon and calcic horizon. These investigations will be supported by absolute dating (radiocarbon, thermoluminescence, 234U 230 Th) and by morphostratigraphic relations.

Learning about the period of fan construction of large alluvial fans in the Playa El Fresnal and environmental conditions during that time, are valuable for understanding late Quaternary global change in the presently arid northern Mexico.

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