Drainage and base-level adjustments during evolution of a late Pleistocene piggyback basin, Eastern Cordillera, Central Andes of northwestern Argentina

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ABSTRACT

In northwestern Argentina, mid-Pleistocene out-of-sequence thrusting further disrupted the Andean foreland, giving rise to the Lerma piggyback basin within the Eastern Cordillera. Emergent topography along the eastern edge of the basin, as well as in its interior, interfered with preexisting eastward-flowing river courses. In the northern part of the Lerma basin, rivers temporarily incised across the new topography, yielding wind and water gaps, and in places preserving straths with treads tilted upstream, revealing their tectonic origin. Application of Hack's law shows correspondence between the active and the abandoned channel profiles. Bed profiles of wind gaps are distinct from those of nearby consequent streams. Defeated and deflected northern streams coalesced into a trunk stream, which maintained an open channel across the eastern bounding ranges. River defeat may have been related to rain shadowing by the growing topographic barrier and retention of easterly derived moisture outside the Lerma basin. In the southern Lerma basin, river courses were not generally capable of sustaining active water gaps. Instead, they were deflected southward, and their discharges fed ancient Lake Lerma. Lake expansion ensued until water level reached a structural low, through which lake waters outflowed from the basin and subsequently incised across the eastern bounding ranges. The relative success of northern rivers in incising across the rising topographic barrier is mainly attributed to their greater channel gradients at the point of incision, combined with high rainfall levels. Longitudinal channel profiles show that rivers in the northern Lerma basin had approached their base level of erosion before uplift of the eastern bounding ranges. After this disturbance, the system continues to approach a new base level of erosion, modified by sediment aggradation within the basin. Speculatively, mid-Pleistocene out-of-sequence thrusting is attributed to basement uplift in the distal foreland.

INTRODUCTION

Northwestern Argentina consists of, from west to east, the Puna, Eastern Cordillera, and Subandean Ranges tectonostratigraphic zones (Figs. 1A, 1B, and 1C). In Eocene times, this region was the site of a continuous backarc foreland basin that underwent progressive structural segmentation (Jordan and Alonso, 1987; Deeken et al., 2006). Uplift of the Puna took place in Eocene to early Miocene times (Hernández et al., 1999a; Hongn et al., 2007), followed shortly after by uplift of the western ramparts of the Eastern Cordillera (Hilley and Strecker, 2005; Bywater Reyes et al., 2010). By the middle Miocene, an extensive piedmont, traversed by east-southeast–flowing streams, descended toward the South American craton (Monaldi et al., 1996; Hain et al., 2011).

Despite along-strike homogeneity in the regional compressive stress field (Kendrick et al., 2001; Riller and Oncken, 2003), the foreland developed contrasting structural styles during late Miocene to recent evolution. North of ~24°S, décollement zones in a >15-km-thick Paleozoic to Cenozoic sedimentary succession isolate upper-crustal from lower-crustal shortening, forming a thin-skin structural style characterized by eastward-younging, east-vergent thrust faults cutting through a 7-km-thick late Miocene to recent sedimentary sequence underlying a continuous foreland (Fig. 2; Mingramm et al., 1979; Echavarría et al., 2003).

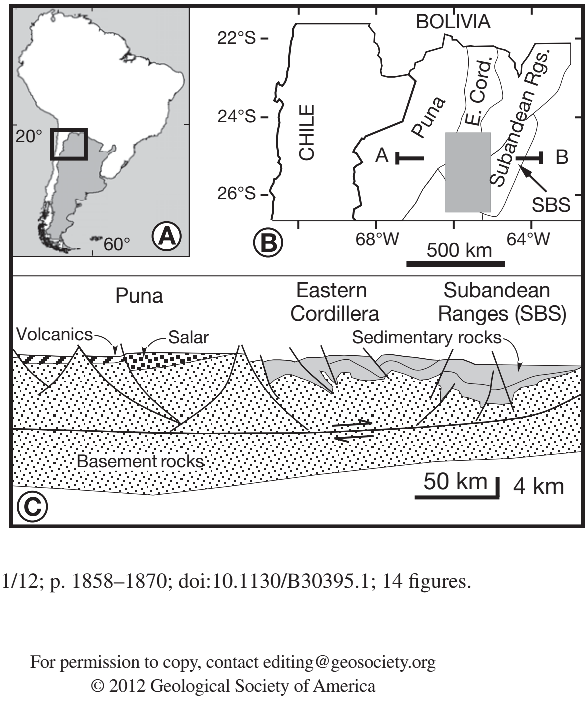

Figure 1. Geographical and geological setting of the study area. (A) General location, with Argentina shaded. Rectangle indicates extent of inset B. (B) Tectonostratigraphic zones mentioned in the text. Gray rectangle indicates extent of Figure 2. Line AB refers to cross section in inset C. SBS—Santa Barbara System. (C) Schematic structural cross section traversing the study area at latitude 25°S (modified from Muñoz et al., 2005).

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GSA Bulletin; November/December 2012; v. 124; no. 11/12; p. 1858–1870; doi:10.1130/B30395.1; 14 figures.

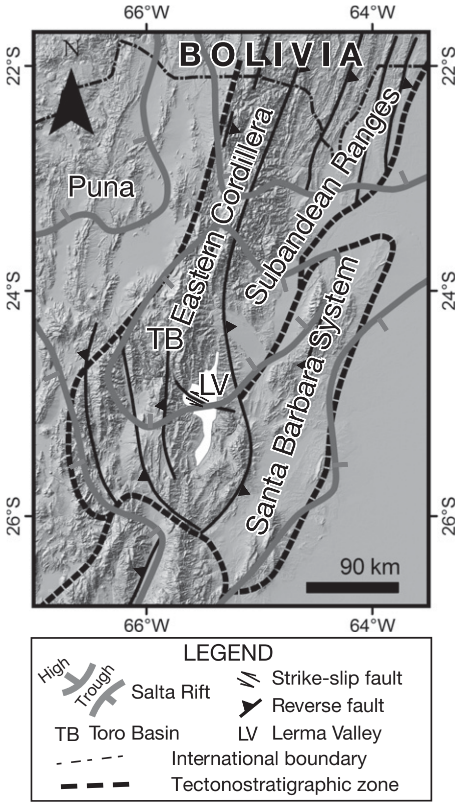

Figure 2. Hillshade view of northwestern Argentina and southernmost Bolivia, extracted from ASTER 30 m digital elevation model scenes (location in Fig. 1B), and structural and morphological setting of the Lerma Valley (white area in center). The paleogeographic highs and troughs of the Salta Rift are related to the geometry of the tectonostratigraphic zones and the location of major faults. The Eastern Cordillera widens, and develops a bivergent fault system, over the central Salta Rift high and main trough, and the Santa Barbara System of the Subandean Ranges is set on the inverted eastern branch of the Salta Rift trough (cf. Grier et al., 1991).

South of ~24°S, the stresses acted upon a much shallower basement with deep-seated weaknesses inherited from Paleozoic shear zones and Cretaceous–Paleogene extensional faults (Figs. 1C and 2; Grier et al., 1991; Hongn et al., 2010). Conditioned by favorably oriented weaknesses, the stresses resolved into strike-slip and reverse faulting oblique to the axis of the Andean orogen and bivergent high-angle reverse faults, set in a thick-skin structural style that characterizes the wider, southern reaches of the Eastern Cordillera and the southern segment of the Subandean Ranges, for this reason distinguished as the Santa Barbara System (Figs. 1B and 1C; Mon and Salfity, 1995; Kley et al., 2005; Acocella et al., 2011). The late Miocene to recent deposits (<3 km thick) underlie a broken foreland characterized by basement-cored uplifts (Grier et al., 1991). The largest of the uplifts is related to the Lerma piggyback basin, the sedimentary fill of which is partly preserved in exposures and the subsurface in the structural Lerma Valley (Fig. 2), and it is the topic of this study.

Comparing continuous and broken forelands, Strecker et al. (2012) pointed out that broken forelands tend to develop smaller and more irregularly distributed depocenters, separated by steeper topography for which the location is strongly determined by deep-seated, inherited geologic structures. Further detailed knowledge is needed on broken forelands in terms of hinterland-craton connectivity and sediment-trapping efficiency, the influence of topographically induced microclimates on sediment dynamics, and the relation between basin-floor aggradation and stream incision and diversion. This study of the Lerma basin, a major component of the late Pleistocene broken foreland in northwestern Argentina, contributes to that end.

This paper describes the evolution of the drainage network in the Lerma basin during the late Pleistocene. This basin in part maintained fluvial connection with the Subandean zone through incision, diversion, and concentration of water discharges in a trunk stream, while simultaneously another part evolved into an internally drained system and was flooded by waters of ancient Lake Lerma (Malamud et al., 1996). Such contrasting behavior makes the Lerma basin an interesting area to study the controls on incision and diversion. Topics addressed are (1) the interaction between the topographic elements and the drainage system, as well as the tectonic and sedimentary processes related to the evolution of the Lerma basin, (2) the effect of topographic changes on the base level of erosion for rivers in the Lerma basin, (3) basinwide and local controls on basin-floor aggradation, (4) the response of stream channels to topographic changes in terms of equilibrium profiles, and (5) the interplay among river gradients, rainfall climate, and inherited structural controls on basin geometry. The aims of this study are: (1) to reconstruct the changes in the drainage network and establish their relative timing; (2) to explore the structural, lithologic, and climatic factors controlling incision and diversion of the river courses, including the influence of inherited deep-seated structures; (3) to describe the influence of changes in base level on the development of the antecedent and subsequent channels; and (4) to discuss the degree to which the fluvial system has attained morphologic equilibrium in the past and at present.

GEOLOGIC SETTING AND PALEOCLIMATE

The Lerma Valley is a north-south–oriented structural depression measuring 110 km in length and 30 km at maximum width (Fig. 2). The valley is bounded to the west by the Lesser and Obispo Ranges (summits ~4800 m; all altitudes refer to sea level), to the northwest by the Vaqueros Range (summits ~1900 m), and to the east by the Mojotoro (summits ~1900 m) and Castillejo Ranges (summits ~2000 m; Fig. 3A). The Lesser and Mojotoro Ranges consist of Precambrian–Lower Cambrian, marine, low-grade metapelites of the Puncoviscana Formation, unconformably overlain by Cambrian–Ordovician shallow-marine quartzite and shale (Figs. 3 and 4A; Turner and Mon, 1979). Near the center of the Lerma Valley, the isolated Cerrillos Hills, a doubly plunging, faulted anticline exposing Puncoviscana Formation, Lower Paleozoic, and Salta Group rocks, rise 200 m above the surrounding valley floor (Fig. 3A).

Shortly south from the Cerrillos Hills runs the Toro Lineament, a major fault zone oblique to the Andean orogen axis, which separates sectors of the Lerma Valley having contrasting stratigraphic and structural characteristics (cf. Ramos, 1999). South of the Toro Lineament, Lower Paleozoic strata are not exposed, and the Precambrian–Lower Cambrian substrate is unconformably overlain by a thick sequence of Cretaceous–Eocene continental rift deposits of the Salta Group, and Oligocene–Lower Pleistocene alluvial deposits of the Oran Group (Figs. 3A and 4B; Vergani and Starck, 1989). The Toro Lineament reflects the former structural boundary between the Salta Rift trough, to the south, and a persistent basement high to the north (Fig. 2; Grier et al., 1991; Hernández et al., 1999b; Kley et al., 2005). The Salta Group deposits wedge out northward; an outlier crops out in the Cerrillos Hills.

The Lerma Valley is widest in its central sector and wedges out to the north, constricted between the Vaqueros and the Mojotoro Ranges, and to the south, enclosed by the Obispo and Castillejo Ranges. The greater width comes from a deep and wide westward re-entrant in the internal mountain front–piedmont junction (nomenclature from Bull, 2007). The valley floor dips east-southeastward ~0.7°. The valley is almost entirely filled by conglomeratic deposits resting with sharp angular unconformity on Oran Group and older rocks; a minute proportion of the valley fill, <1% by volume, is made up of lacustrine beds representing ancient Lake Lerma. The post–Oran Group strata in the Lerma Valley are herein designated as the Lerma Valley group. The coarse-grained sedi-

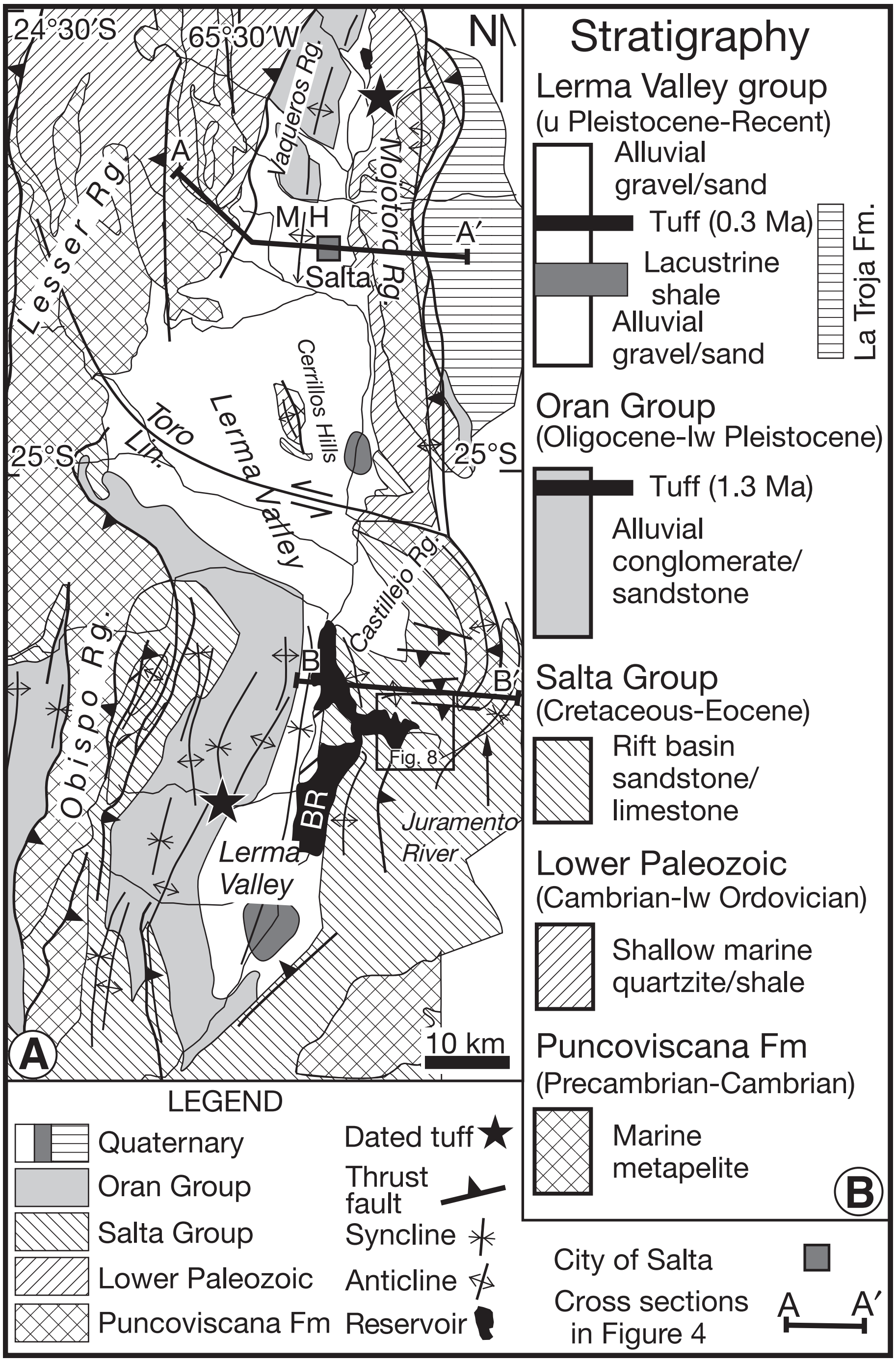

Figure 3. (A) Geological map for the Lerma Valley (MH—Medeiros Hills; BR—Belgrano reservoir; data from Ruiz Huidobro, 1955, 1968; Vergani and Starck, 1989; Mon et al., 2004; Aparicio González et al., 2010). (B) Schematic stratigraphic column. Hatch patterns in map and column are identical except for the tuff beds, indicated by stars in map.

ments in the Lerma Valley group were mostly derived from the Vaqueros, Lesser, and Obispo Ranges, as evidenced by the large alluvial fans attached to these highlands. On the same basis, the narrow alluvial apron attached to the western flank of the Mojotoro and Castillejo Ranges indicates that the detrital contribution from this source was minor. A tuff intercalated in the Piquete Formation (uppermost Oran Group; Mingramm et al., 1979), exposed to the west of the Belgrano reservoir (southern star in Fig. 3A), yielded an age of 1.3 ± 0.2 Ma (zircon fission track; Malamud et al., 1996), and this sets a maximum age for the Lerma Valley group deposits, not considering the time involved in folding and erosion of the substrate. Another tuff, intercalated in colluvial and fluvial deposits of a fill terrace attached to the western flank of the Mojotoro Range in northernmost Lerma Valley, and lacking evidence of tectonic tilting, was dated in 0.33 ± 0.1 Ma (northern star in Fig. 3A; zircon fission track; Malamud et al., 1996).

A three-dimensional gravity survey and vertical electric sounding (VES) in the northern Lerma Valley revealed Lerma Valley group thicknesses of up to 900 m, with depocenters located southwest and south from the Medeiros Hills and west of the Cerrillos Hills (Figs. 5A and 5B; Colombi et al., 1999). The isopach map and a VES cross section (Fig. 5C) indicate that the thickness of the valley fill decreases as the Mojotoro Range is approached. The valley fill may not, however, taper out completely, because water wells and a seismic-reflection survey near the foot of the Mojotoro Range reveal thicknesses in excess of 150 m (González Bonorino et al., 2003; González Bonorino and Abascal, 2012).

Neotectonic activity is documented by ongoing seismicity and deformation of valley fill strata. One powerful (M = 6.3), shallow (9.5 km deep) earthquake, with the epicenter 7 km north of Salta City, occurred in 2010 (Fig. 6; U.S. Geological Survey Shakemap site http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010tfc3.php). This event can be related to the thrust fault along the eastern flank of the Mojotoro Range (F in Fig. 4A; see following section for further details on this fault). Two other, deeper and weaker (M = 3.5 and M = 4.6) events may be related to the same thrust fault, but overall seismic activity in the northern Lerma Valley and Mojotoro Range is low. In fact, in a broader study of seismic activity in northwestern Argentina, Colombi et al. (2002) concluded that the northern Lerma Valley is aseismic. Significant neotectonic activity is concentrated around the Toro Lineament. Earthquake epicenters cluster about this feature on the western flank of the valley (Fig. 6), and faulted and folded strata of the Lerma Valley group occur in areas adjacent to this fault zone (García et al., 2011). More regionally, however, deeply entrenched alluvial fans originating in the southern Lesser Range suggest mild tectonic activity (cf. Bull, 2007).

Mojotoro and Castillejo Ranges

The Mojotoro Range is up to 30 km wide and shows an asymmetric topographic profile, with a narrow, steep western flank and a wide,

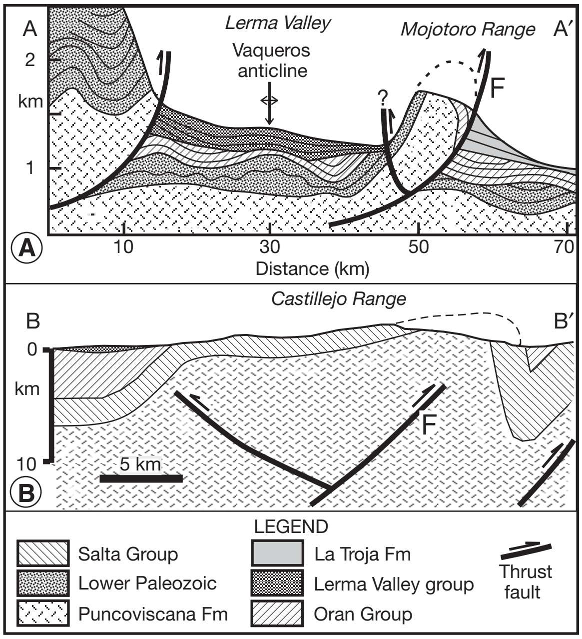

Figure 4. (A) Cross section in the northern Lerma Valley and Mojotoro Range (A-A′ in Fig. 3A), adapted from Ruiz Huidobro (1955, 1968). (B) Cross section in the central Castillejo Range (B-B′ in Fig. 3A), adapted from Mon et al. (2004). In both panels, F refers to the range-bounding fault for which the surface exposure is mapped in Figure 3A.

gently sloping eastern flank (Fig. 4A). The main support for the Mojotoro Range is an east-vergent and slightly overturned, thrust-faulted anticline with a core of chevron-folded strata of the Puncoviscana Formation and a 1.5-km-thick cover of Cambrian–Ordovician quartzites alternating with shales (Figs. 3A and 4A; Ruiz Huidobro and González Bonorino, 1953; Ruiz Huidobro, 1955, 1968). The width of the anticline at ground level is ~10 km. The thrust fault that initiated the Lerma piggyback basin dips 75° at the surface (Ruiz Huidobro and González Bonorino, 1953); the 9.5-km-deep earthquake focus mentioned previously suggests that the fault plane becomes shallower with depth. Attached to, and eroded from, the eastern flank of the elevated block, there is a deeply dissected eastward-thinning wedge of Pleistocene alluvial-fan deposits designated as La Troja Formation by Hain et al. (2011; Fig. 3A). The straight western boundary and steep western flank of the Mojotoro Range suggest the presence of a high-angle fault, tentatively indicated in Figure 4A as antithetic to the range-bounding thrust.

The Castillejo Range is underlain by a continuation of the east-vergent, thrust-faulted anticline underlying the Mojotoro Range, though strongly modified by superimposed transverse folds and faults originated in the reactivation of buried Cretaceous rift faults and movement along the Toro Lineament (Fig. 3A; Vergani and Starck, 1989; Mon et al., 2004). The wedge of La Troja alluvial-fan deposits disappears toward the south. In part, this may reflect the marked southward decrease in rainfall levels (Fig. 7A). The thrust fault bounding the Mojotoro and Castillejo Ranges becomes a blind thrust south of the Toro Lineament (Figs. 3A and 4B; Kley and Monaldi, 1999; Mon et al., 2004).

The presence of Oran Group strata with comparable thicknesses on both flanks of the Mojotoro-Castillejo anticline (Vergani and Starck, 1989; Hain et al., 2011) indicates folding and uplift largely later than 1.3 Ma. In the north, the tectonically untilted 0.33 Ma terrace deposits attached to the western flank of the Mojotoro Range approximately mark the cessation of uplift. Terminal uplift of the Castillejo Range is assumed to have been approximately coeval with that of the Mojotoro Range. During the west to east segmentation of the foreland, closure of the Lerma basin at ca. 1 Ma was preceded by closure of the Toro intramontane basin in the western Eastern Cordillera at ca. 6.4 Ma (TB in Fig. 2; Hilley and Strecker, 2005).

The out-of-sequence contraction that occurred in the Lerma piggyback basin and uplift of the Mojotoro-Castillejo Ranges may have been related to mild basement upwarp in the distal foreland, as evidenced by base truncation of the foreland wedge in the Santa Barbara System (cf. Salfity et al., 1993). Analog modeling of foreland thrust belts led Nieuwland et al. (2000) to conclude that a basement high ahead of the thrust front favors out-of-sequence thrusting. Speculatively applying Nieuwland et al.'s (2000) model, basement uplift in the area of the Santa Barbara System would have hindered advance of the thrust front, favoring out-of-sequence thrusting.

Vaqueros Range and the Medeiros Hills

The Vaqueros Range consists of moderately indurated coarse-grained alluvial strata of the Oran Group forming a north-south–trending anticline showing slight eastward asymmetry and plunging gently to the south beneath a 70-m-thick unit of coarsely bedded sandy gravel attributed to an ancient Lesser River alluvial fan (Figs. 3A, 4A, and 7B; Medina, 1981; Gallardo et al., 1996; Monaldi et al., 1996; this work). The sandy gravel beds rest with sharp angular unconformity on folded Oran Group strata and are part of the Lerma Valley group. Imbricated clasts indicate southward to southeastward paleoflow (Georgieff and González Bonorino, 2004). The abandoned fan surface rises close to 200 m above the adjacent floor of the Lerma Valley and underlies the Medeiros Hills (MH in Fig. 3A).

Paleoclimate

Present climate in the studied segment of the Eastern Cordillera is temperate with marked north-south and west-east rainfall gradients (Fig. 7A; Bianchi and Yáñez, 1992; Bianchi, 2005; Alonso et al., 2006; Strecker et al., 2007). Precipitation is concentrated in the austral summer months and falls largely in thunderstorms (Bianchi et al., 2005). Along the eastern slopes of the Lesser and Obispo Ranges, rainfall amount varies from 1400 mm/yr in the north to 600 mm/yr in the south, and from <600 mm/yr in the west to 1400 mm/yr in the east, across the ranges, reflecting a rain-shadow effect. Within the Lerma Valley, precipitation mostly ranks between 600 and 800 mm/yr. Outside the Lerma Valley, along the eastern flank of the Mojotoro Range, rainfall amount shows a maximum of 1200 mm/yr (precipitation values taken from Bianchi, 2005). Bianchi et al. (2005) estimated that rain shadowing in this region becomes effective where crest-line elevations exceed 1000 m.

Alonso et al. (2006), based on an exhaustive synthesis of late Cenozoic paleoclimate data from localities in the Puna and western Eastern Cordillera, concluded that the regional pattern of wind circulation and precipitation in the Pliocene–Pleistocene may have been similar to that at present, and strongly modulated by orographic rain-shadow effects. Assuming that this conclusion can be extended to the Lerma basin, it is herein tentatively inferred that precipitation in the basin would not have been less than at present (cf. Fig. 7B). In fact, it may have been higher before the rising Mojotoro-Castillejo Ranges began to retain easterly moisture on their eastward-facing slopes.

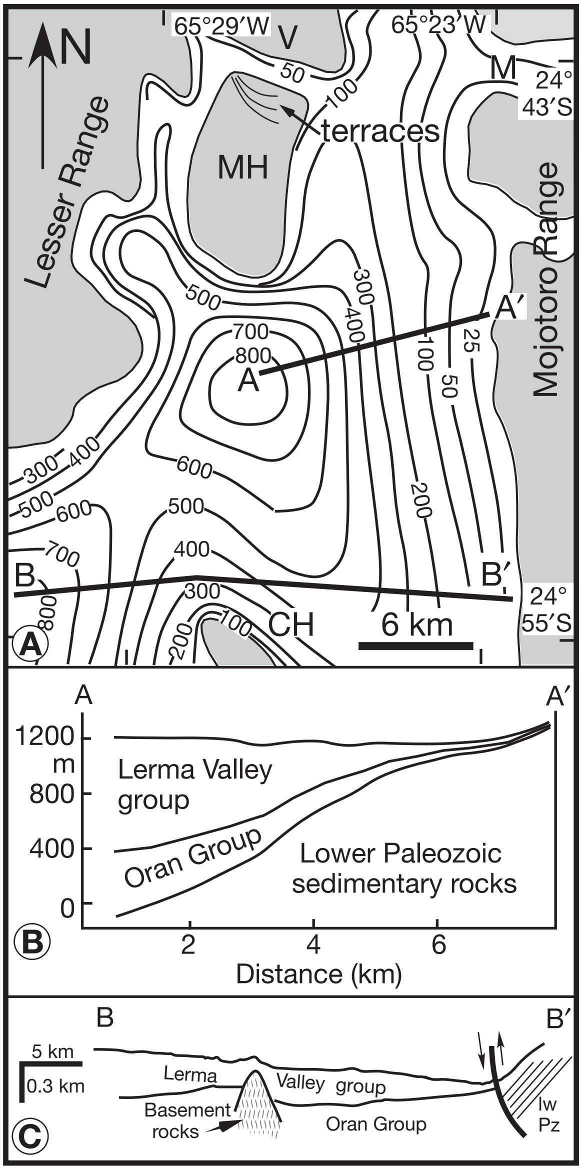

Figure 5. Thickness of the Oran Group and Lerma Valley group deposits in the northern Lerma Valley. (A) Isopach map (in m) based on three-dimensional gravimetry, taken from Colombi et al. (1999). V—Vaqueros Range, M—Mojotoro River, MH—Medeiros Hills, CH—Cerrillos Hills. Also shown is position of the fluvial terraces on the north flank of the Medeiros Hills. Elevated areas are grayed. (B) Cross-section A-A′, based on the gravimetric data in Colombi et al. (1999). (C) Cross-section B-B′, based on vertical electric soundings (VES), modified from García (1988). lw Pz—lower Paleozoic sedimentary rocks.

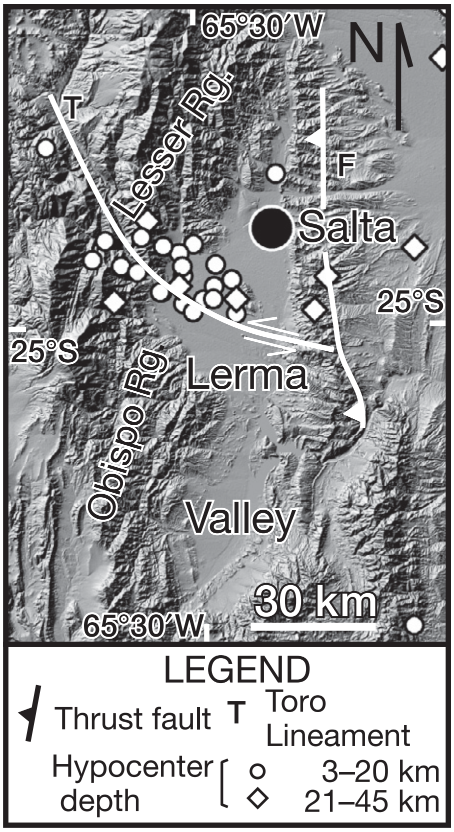

Figure 6. Hillshade representation of the Lerma Valley (central flat region) and surrounding ranges. F indicates the range-bounding thrust fault that gave rise to the Lerma piggyback basin. Earthquake epicenters are shown for historical earthquakes of magnitude >3 occurring at crustal depths, grouped in shallow (depth 3–20 km) and deep (depth 21–45 km) (data from U.S. Geological Survey, http://earthquake.usgs.gov, and Instituto Nacional de Prevención Sísmica [INPRES], http://www.inpres.gov.ar).

MODERN AND ANCIENT RIVER COURSES IN THE LERMA VALLEY

Modern Drainage

The drainage network in the Lerma Valley is organized into two subbasins, with a subtle divide at the latitude of the City of Salta. In the northern subbasin, the Santa Rufina and Wierna Rivers are tributaries of the Caldera River (Fig. 7B), which, in turn, joins the Lesser-Vaqueros River to become the Mojotoro River that crosses the Mojotoro Range. Catchment areas for the Santa Rufina, Wierna, and Lesser-Vaqueros Rivers range between 240 km^2 and 400 km^2 and show relatively steep average slopes between 16° and 22° (measured on ASTER 30 m digital elevation model [DEM] images). The Wierna River incises ~150 m into Oran Group strata as it crosses the Vaqueros Range anticline. The Lesser River runs along the fault contact between uplifted basement rocks in the Lesser Range and Oran Group strata in the Vaqueros Range, and incises into deposits in the apex of the Lesser River alluvial fan. The Vaqueros River incises across 70 m of Lesser River fan deposits and ~15 m into underlying Oran Group beds. The Mojotoro River incises 800 m below the crest line of the Mojotoro Range, cutting into Puncoviscana Formation and Lower Paleozoic beds in the overturned anticline. The Mojotoro channel, noticeably straight, narrows to 60 m where it cuts across the quartzite-rich limbs of the anticline and widens to more than 1000 m where it intersects the more erodible Puncoviscana slates in the anticline core and the Pleistocene alluvial deposits farther downstream. Where they cross the Lerma Valley, the Santa Rufina, Wierna, and Arenales Rivers do not erode more than 5–10 m into the Lerma Valley group deposits.

The Santa Rufina, Wierna, and Vaqueros Rivers develop alluvial fans in their lower reaches (Fig. 7B); deposition backfilled the river channels for up to 9 km. The Lesser River, and the Santa Rufina and Wierna Rivers upstream from the terminal fans, carry gravelly bed load and fit in the "plane bed" channel type of Montgomery and Buffington (1997). The modern channel of the Vaqueros River has a longitudinal gradient of 0.025 (1.4°) and is underlain by alluvium

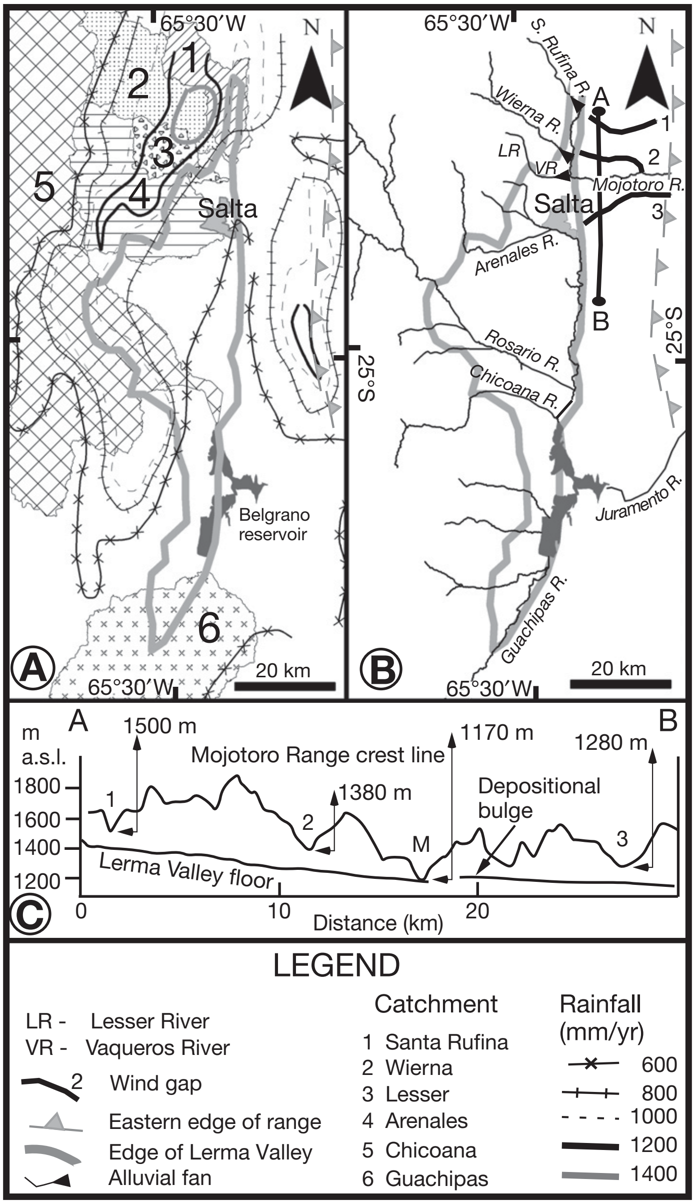

Figure 7. (A) Rainfall distribution (data from Bianchi, 2005) and major catchments in the Lerma Valley. (B) River courses mentioned in the text; line A-B approximately follows the drainage divide supported by the less erodible Lower Paleozoic quartzites. (C) Topographic cross section (A-B) shows wind gaps 1, 2, and 3, and altitudes at the drainage divide. M—Mojotoro River.

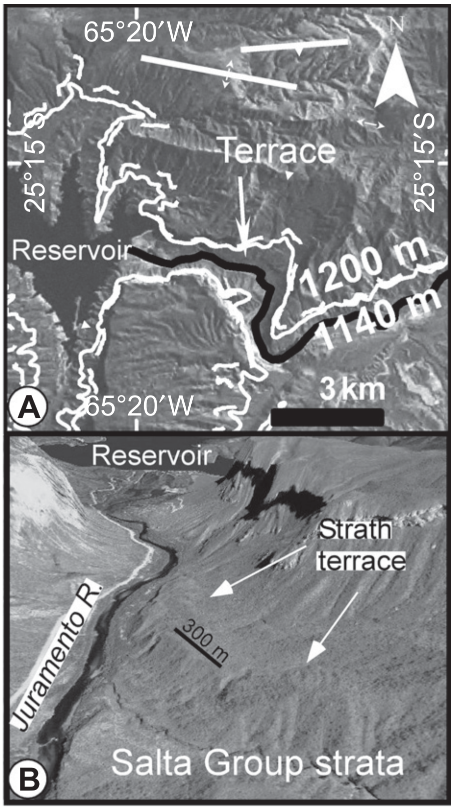

Figure 8. Uppermost reach of the Juramento River. (A) Hillshade view with contour lines for 1140 and 1200 m above sea level (a.s.l.); location shown in Figure 3A. The Belgrano reservoir is the dark area on the left. The Juramento River is the thick black line. Position of strath terrace shown in B is indicated. East-west–oriented faults and folds are related to the Toro Lineament. (B) Oblique view toward the west with strath terrace in foreground. The terrace tread is at ~1050 m. The terrace is carved in sedimentary strata of the Salta Group. Image taken from Google Earth, 25°15′S, 65°20′W, accessed on 10 August 2010.

ranging in thickness from a few meters to more than 50 m (vertical electric soundings in Gutiérrez, 1995); it qualifies as an alluvial channel.

South of the City of Salta, the drainage network is composed of the Arenales, Rosario, and Chicoana Rivers (Fig. 7B). These rivers are deflected southward at the foot of the Mojotoro Range and debouch into Belgrano reservoir; water then exits Lerma Valley as the Juramento River, which has incised ~150 m into folded and faulted Salta Group strata (Fig. 8A). Drainage areas for the southern rivers are considerably larger than for the northern ones, namely, Arenales 575 km^2, and Chicoana-Rosario combined 1711 km^2, and although average basin slopes are similar, 16.7° to 18.8°, they have long low-gradient reaches across the Lerma Valley. In the far south, the Guachipas River flows from south to north into the Lerma Valley but is not discussed in this paper.

Paleodrainage

In discussing the organization of drainage in the Lerma Valley during the late Pleistocene, it will be assumed that the stream system in the source areas, that is, on the steep eastern slopes of the Obispo and Lesser Ranges, has undergone minor changes since the early Pleistocene, apart from parallel retreat. This assumption has support in the fact that stream power diminishes toward the headwaters (cf. Bull, 2007, p. 31). It will also be assumed that rainfall distribution was similar in the late Pleistocene to that observed at present and that rainfall levels were at least as high as at present.

Wind Gaps and Other Abandoned Stream Channels

Wind gaps on the Mojotoro Range indicate incision into the emerging topographic barrier (Fig. 7B; Ruiz Huidobro, 1968). Visual inspection suggests correlation of wind gaps with former extensions of the Santa Rufina River (wind gap 1), the Wierna River (wind gap 2), and the Arenales River (wind gap 3). The upstream ends of the wind gaps align with the drainage divide, which is underlain by the quartzite-rich western limb of the anticline (Fig. 9). A topographic cross section along the drainage divide was extracted from an ASTER 30 m DEM. The maximum elevations of the wind gaps are: 1500 m for wind gap 1, 1380 m for wind gap 2, and 1280 m for wind gap 3 (Fig. 7C). Relative to the adjacent floor of the Lerma Valley, the height differences are: 100 m for gap 1, 120 m for gap 2, and 120 m for gap 3.

Geoelectric profiles in Gutiérrez (1995) allow computation of the slope of the buried bedrock channel of the Vaqueros River, which locally attains 0.048 (2.7°). Between the latitude of the City of Salta and that of the Cerrillos Hills, abandoned channels related to the ancient Arenales River reflect northward migration as a reaction to the rise of the Cerrillos Hills, as previously observed by Ruiz Huidobro (1968).

Lake Lerma

Rivers in the southern subbasin fed Lake Lerma, the deposits of which are represented by a thin (~25 m thick) and narrow (<10 km wide) clay-rich lithosome with freshwater fauna (Gallardo et al., 1996). These deposits are adjacent to the Mojotoro Range and extend from the latitude of the Cerrillos Hills to the southern end of Lerma Valley (Fig. 3A; Gallardo et al., 1996; Malamud et al., 1996).

Medeiros Hills Fluvial Terraces

On the northern slope of the Medeiros Hills, a flight of six unpaired fluvial terraces, designated T1 to T6, from older to younger, descends to the right margin of the Vaqueros River (Figs. 5A and 10A; Georgieff and González Bonorino, 2005). T6 is the modern terrace of the Vaqueros River, and T5 has been altered by human construction and occupation; only terraces T1 to T4 are considered herein. The original terrace morphology has been modified by minor hillslope and fluvial erosion. The original gravel-topped tread surfaces are now largely mantled by fine-grained eolian sediment.

Straths T1 to T4 are carved into the Lesser River alluvial-fan deposits and covered by several meters of sand/gravel deposits with imbricated clasts indicating paleoflow parallel to the risers. The treads are armored by coarse gravel, including boulders up to 2 m in length. Measurement of long dimensions of the ten largest exposed boulders along 50-m-long terrace reaches yielded the following averages: T1 = 1.4 m, T2 = 1.4 m, T3 = 1.2 m, and T4 = 1.1 m. Boulders 1–2 m in long dimension were not observed in the Lesser River fan or in the immediately underlying Oran Group deposits, but they are common in the steep bedrock channels of the Lesser River and other nearby streams.

Topographic cross sections were surveyed parallel and perpendicular to the risers to: (1) determine if the terrace treads are tectonically tilted, and (2) compare the terrace longitudinal gradients with that of the modern Vaqueros River. Longitudinal profiles for T1 to T4 show subparallel eastern reaches but differ in the inclination of the western reaches, with T1 and T2 dipping to the west and T3 and T4 subhorizontal (Fig. 10B). Profiles perpendicular to the risers show treads that slope inward, that is, toward the next older terrace (Fig. 10C). The slope increases with terrace age.

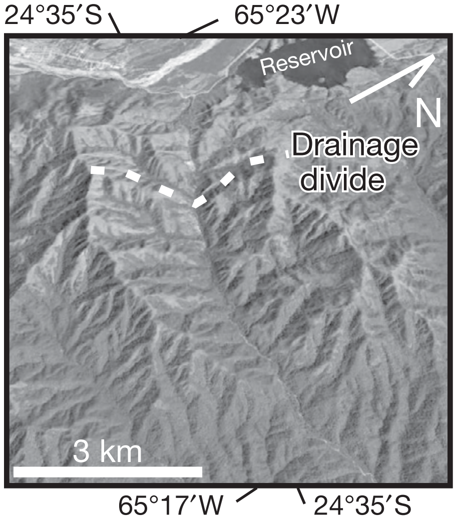

Figure 9. Upstream view of wind gap 1. Downstream end of Santa Rufina alluvial fan appears in upper left of image. Small reservoir (mapped in Fig. 3A) is shown in upper right of image. Dashed white line indicates trace of drainage divide. Oblique image taken from Google Earth, 24°15′S, 65°20′W, accessed on 10 August 2010.

Longitudinal Stream Profiles

The continuous Lesser-Vaqueros-Mojotoro river channel connects the headwaters with the Subandean plains. Following Hack (1973) and Bull (2007), stream-gradient indices were computed for this river along almost 40 km of channel length (Fig. 10A). The Lesser River runs north-south and turns to an east-west orientation at its confluence with the Castellanos River (Fig. 10A) and becomes the Vaqueros River. Stream-gradient indices for the Lesser River are high and do not fall on a straight line on a semilogarithmic plot (Figs. 11A and 11B). The Vaqueros-Mojotoro River segment shows fairly constant gradient indices that approach a straight line on a semilogarithmic plot (Fig. 11B). Slight departure from a linear trend occurs in the reach extending between the exit from the Vaqueros Range and the westernmost narrows in the Mojotoro River. Along this reach, gradient indices first increase, then decrease where the Vaqueros meets the Caldera River before entering the Mojotoro Range, and finally increase again as the channel traverses the gorge.

The longitudinal profile of the Wierna River and its postulated former continuation along the Gallinato wind gap (wind gap 2 in Fig. 7B) is plotted in Figure 12A. From the drainage divide to river km 16, the Wierna River channel is convex, presumably reflecting the dominance of nonfluvial processes (cf. Wobus et al., 2006). From river km 16 to km 40, the channel profile is smoothly concave; elevation versus natural logarithm of distance from the water divide plot on a straight line, suggesting that this reach approaches an equilibrium profile. At about river km 40, the apex of the Wierna alluvial fan is observed, extending to the foot of the Mojotoro Range. The profile of the wind gap reach is less concave (concavity index = 0.33) than that of a nearby consequent stream channel (concavity index = 0.41; concavity indices were measured with the program StreamProfiler; Whipple et al., 2007; Fig. 12C). Where it crosses the thrust fault, passing downstream from indurated Lower Paleozoic quartzites and shales to Pleistocene fanglomerates, the channel steepens (Fig. 12B). The profile of the Santa Rufina River–wind gap 1 channel is similar in shape to that of the Wierna–wind gap 2 channel (Figs. 12A and 12B). To explore further the morphological relation between the active Wierna River channel and the Gallinato wind gap, Hack's law (Hack, 1973) was applied. Data from km 16 to km 40 were used to calibrate Hack's equation, and the ideal equilibrium profile downstream from km 40 was computed (dots in Fig. 12A). The wind gap and the equilibrium profiles are close to parallel, the former ~220 m higher, without evidence for tilting during uplift.

DISCUSSION

We analyze the interpretation of terrace morphology first, before dealing with the succession of changes in the drainage pattern in the Lerma

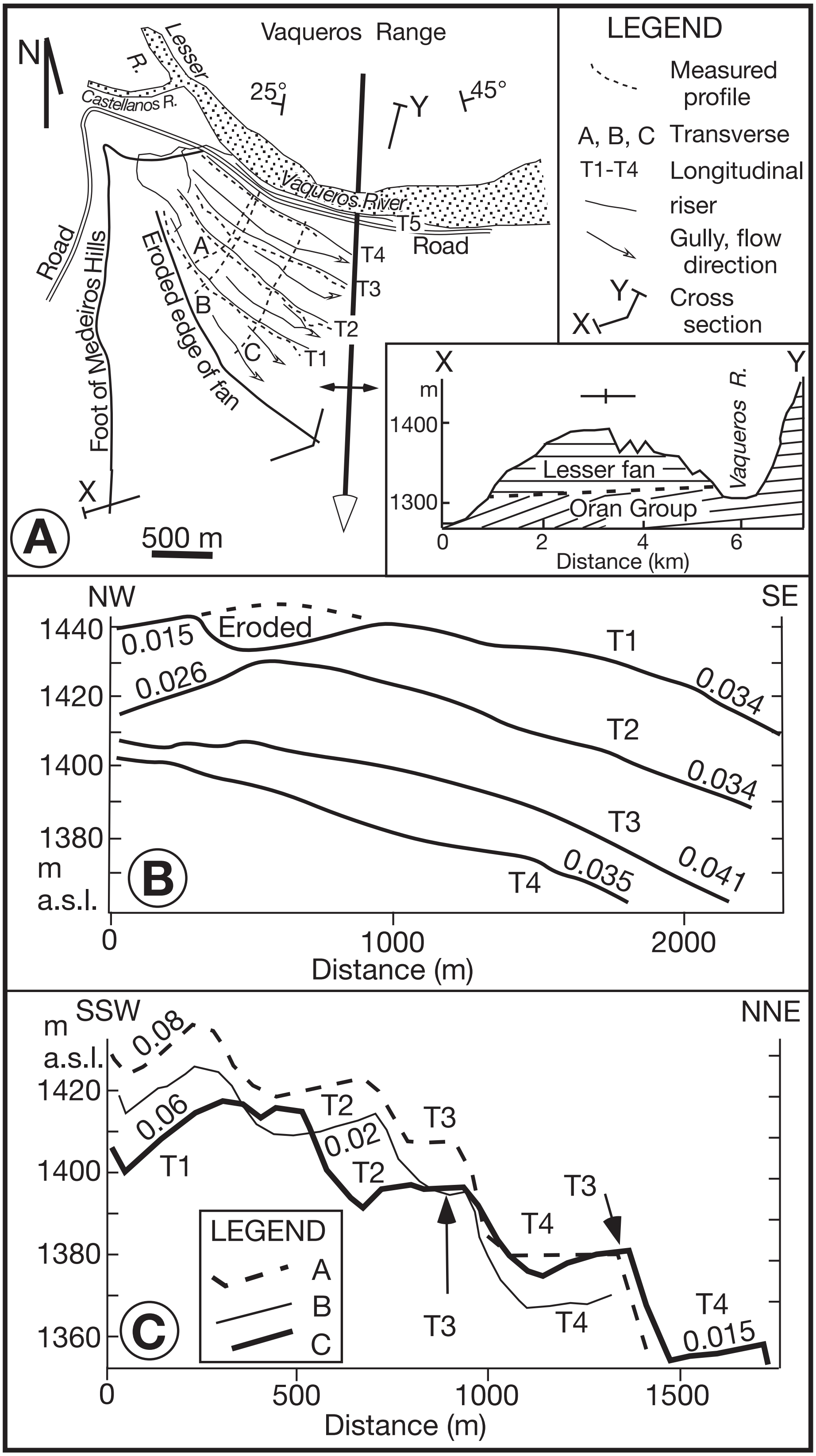

Figure 10. Fluvial terraces on the northern flank of the Medeiros Hills. (A) Location map showing terrace edges, major gullies, and traces of surveyed profiles. Inset shows topographic and geologic cross-section X-Y; bedding dip is schematic; note apparent dip change. (B) Longitudinal topographic surveys. (C) Transverse topographic surveys; A, B, and C refer to profiles mapped in A. Decimal numbers are tread gradients in rise over run. Topographic surveys were carried out with hand-held and differential global positioning instruments (GPS), recording in continuous mode and averaged waypoints.

Valley and their controls. Finally, we discuss the effects of base-level changes and of inherited basement structures on river profiles.

Terrace Development

Development of the Lesser River alluvial fan requires previous diversion of the ancient Lesser River southward, and, thus, it postdated initial folding of the Vaqueros anticline. The fan deposits accumulated on the folded and eroded Oran Group strata. Renewed uplift of the Vaqueros anticline caused incision into the fan deposits, cutting off coarse sediment supply to the fan surface and initiating erosion of straths T1 to T4.

The longitudinal gradients of the terrace treads differ in the inclination of the upstream reaches, with T1 and T2 showing marked westward tilting and T3 and T4 being subhorizontal (Fig. 10B), and in all cases departing from the expected gradual downstream descent. This departure would reflect tectonic tilting of the western limb of the Vaqueros anticline. The downstream reaches of the longitudinal profiles are approximately parallel, with slopes similar to the slopes of the bedrock channels of the ancient Vaqueros River (<0.048) and that of the Wierna River above the terminal fan (0.035). Thus, these terraces were carved by steep flows competent to transport the large boulders armoring the treads. Profiles normal to the risers show that the treads dip away from the ancient active river channel by up to 4° and, in addition, show inclinations that increase with terrace age (Fig. 10C). The increase in transverse gradient with terrace age also indicates an increase through time of the structural relief of the southern plunge of the Vaqueros anticline.

The slight decrease in average boulder size from T2 to T4 could be taken to imply diminishing stream power, and although the parallelism

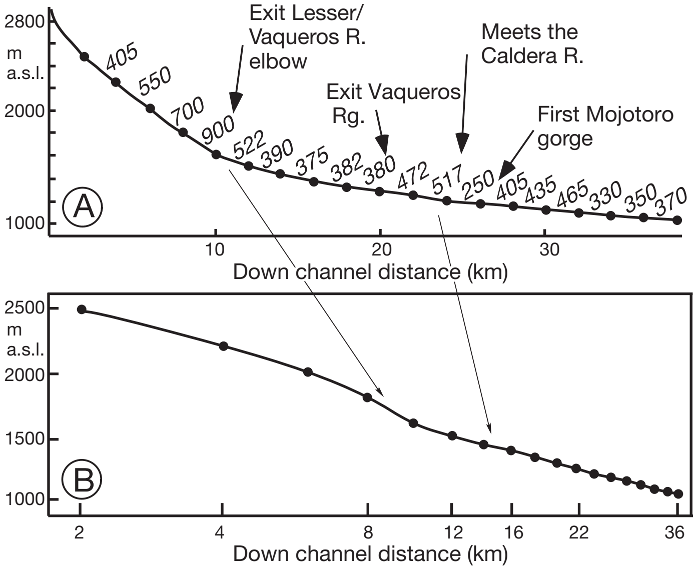

Figure 11. Stream-gradient index plots (Hack, 1973) for the Lesser-Vaqueros-Mojotoro stream course. (A) Gradient indices for 2-km-long consecutive reaches, starting 2 km downstream from the drainage divide. (B) Same data on semilogarithmic plot.

of the downstream gradients in T1 to T4 does not support such a conclusion, the action of climatic stresses concurrent with folding is not discarded.

Development of the Wind and Water Gaps

Before emergence of the Vaqueros and Mojotoro Ranges, river courses flowed east-southeast across the future site of the Lerma basin (Fig. 13A). Uplift of the Vaqueros anticline had two immediate consequences. One was entrenchment of the Wierna River. The other was to collect drainage from the Lesser Range south of the Wierna River and to funnel it along the junction between the upthrusted basement rocks to the west and the western limb of the anticline. The Lesser River alluvial fan developed at the exit from the mountain front (Fig. 13B).

During initial emergence of the Mojotoro Range, the preexisting Santa Rufina, Wierna, and Arenales Rivers incised through an unknown thickness of Oran Group strata and Lower Paleozoic quartzites, into slaty Puncoviscana beds. Wind gap 2, part of the ancient Wierna River, terminates at the present Mojotoro River (Fig. 7B), indicating that a river course existed at that position at the time during which the Mojotoro Range was rising. The most likely explanation for the presence of that stream is that the ancient Lesser-Vaqueros-Mojotoro River had migrated from an east-southeast orientation to a course near its present east-west trend (Fig. 13C). This, in turn, implies that the Medeiros terraces, and consequently the Lesser River alluvial fan, predate emergence of the Mojotoro Range. This conclusion modifies paleogeographic reconstructions assuming uplift of the Mojotoro Range at a much earlier time, in the Pliocene to early Pleistocene, before terrace formation (e.g., Ruiz Huidobro, 1968; Gallardo et al., 1996; Monaldi et al., 1996).

The decreasing absolute elevation of the wind gap floors from north to south (Fig. 7C) may be taken to reflect progressive abandonment of the stream channels in the same direction. Relative to the adjacent floor of the Lerma Valley, however, wind gap heights are similar. The Santa Rufina, Wierna, Vaqueros, and Arenales Rivers are not incised more than a few meters into the valley fill, so the valley floor approximates their ancient local base levels of erosion. In this alternative view, stream diversion, and channel abandonment, could have been roughly synchronous along a 40-km-long mountain front. This may imply accelerated uplift of the Mojotoro Range or, more likely, orographically induced reduction in rainfall amount in the northern Lerma Valley due to rain shadowing by the rising Mojotoro Range. The present elevation of the wind gaps indicates that they developed when the Mojotoro Range had risen to within ~100 m of its present elevation, and thus moisture retention on its eastern flank probably was similar to that observed at present. After being deflected, the Santa Rufina and Wierna discharges coalesced into the Caldera River, reinforced that of the Lesser-Vaqueros-Mojotoro River, and favored the persistence of this outlet as a water gap.

The ancient Arenales River carved the deep wind gap 3 into the rising Mojotoro Range. The position of the gap along the mountain front would have been controlled by the emergence of the Cerrillos Hills, displacing the course of the ancient Arenales River slightly to the north (see abandoned channels in Fig. 13B). Farther south, the Chicoana and Rosario Rivers were incompetent to incise across the rising Castillejo Range. Lake Lerma probably started to fill in at this time (Fig. 13B). Eventually, the Arenales River was itself deflected, and its water discharge was added to that of the Rosario, Chicoana, and other streams; Lake Lerma grew to its maximum extent (Fig. 13C).

The success of the northern rivers (Santa Rufina, Wierna, and Lesser-Vaqueros-Mojotoro), compared to those in the south, in carving antecedent channels across the rising Mojotoro-Castillejo Ranges would reflect larger stream power at the sites of incision derived from two factors. One was that drainage basins for the northern rivers, though smaller in area, received more than twice the amount of annual rainfall. During the early stage of Mojotoro uplift, before it created a rain-shadow effect, the rainfall amount in the Lerma Valley probably was enhanced by the influx of easterly moisture presently retained in the east. Another factor was that the northern rivers reached the rising Mojotoro block along steep bedrock channels. In contrast, rivers flowing across the central Lerma Valley (Arenales, Rosario, and Chicoana) have large drainage basins that compensate for lower rainfall levels, but due to the deep westward reentrant in the mountain-piedmont junction, they flowed over long, low-gradient reaches before reaching the rising Mojotoro bedrock, suffering loss of water by evaporation and infiltration into the porous substrate (Fig. 14A). Their capacity to transport sediment and elevate the valley floor to the level of the rising bedrock would have been hindered. The Arenales River, for instance, occupies a wide fluvial plain below the average level of the Lerma Valley surface, with no evidence of having built an alluvial fan at the foot of the Mojotoro Range. Defeat and deflection of the Arenales River may also have been dictated by the northward expansion of Lake Lerma, further lowering the downstream gradient.

The top of the lacustrine deposits is at ~1140 m, suggesting a minimum lake water level at approximately this altitude (Malamud et al., 1996). The Juramento River crosses the Castillejo Range through a steep-sided escarpment carved in strata of the Salta Group (Figs. 8A and 8B). The 1140 m contour line falls close to the upper lip of the escarpment (Fig. 8A), allowing the inference that Lake Lerma waters reached a spillover level along structural lows

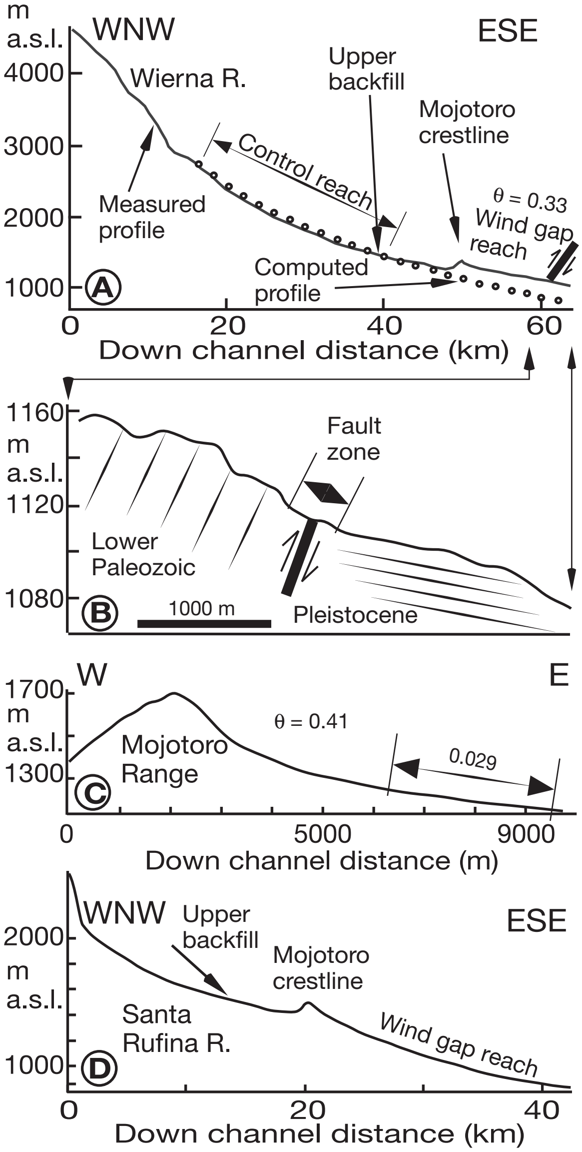

Figure 12. Longitudinal profiles of streams extracted from ASTER 30 m digital elevation models. (A) Wierna River and its former continuation in the Gallinato wind gap (wind gap 2 in Fig. 7B). The "upper backfill" arrow points to the apex of the terminal fan. Small circles show computed equilibrium profile (see text). (B) Profile across the range-bounding thrust fault shows channel steepening. (C) Channel profile of consequent stream located 12 km due north from the Mojotoro River. Profile concavity is greater (0.41) than that in the wind gap reach in inset A (0.33). (Note: Profiles in A, C, and D align on Mojotoro Range crest line.) (D) Santa Rufina River and its former continuation along wind gap 1 (Fig. 7B).

(Mon, 2005) and incised down from there as a subsequent stream, adjusting to the base level in the unbroken foreland to the east. The eastern base level continues to regulate drainage at present. A strath terrace at ~1050 m (Fig. 8B) may reflect a temporary standstill and attainment of base level of erosion. A crude computation of the present-day rate of evaporation over central Lerma Valley (0.9 m/yr), compared with total annual inflow, indicates that expansion of Lake Lerma to an area equivalent to the 1140 m contour line (~640 km^2) would not have been limited by the rate of evaporation (see also Malamud et al., 1996).

The westward re-entrant in the central Lerma Valley is attributed mainly to active faulting associated with the Toro Lineament, which traverses the mountain-piedmont junction. Faulting would have weakened the substrate and favored erosion of a pathway for the Rosario River, the upper reach of which coincides with the trace of the Toro Lineament (Figs. 3A and 7B). Waning activity on the internal range-bounding fault may also have contributed to development of the re-entrant (cf. Bull, 2007).

Separation of northern and southern subbasins can be traced back to before uplift of the Mojotoro Range. A probable explanation is that the ancient Vaqueros-Mojotoro River captured any southbound drainage. Immediately south of the Vaqueros River, near its confluence with the Caldera River, a depositional mound, probably a remnant of the Vaqueros River terminal alluvial fan, rises 15 m above the valley floor (Fig. 7C). The mound would have obstructed southward flow. The accumulation of sediment may have been related to the funneling of sediment through the Medeiros terraces into this area. Groundwater flow is not affected by this divide (Baudino, 1996), indicating that the divide is not due to a subsurface feature.

Quest for Equilibrium

Northern river courses were initially perturbed by the emergence of the Vaqueros anticline, at a time when the Lerma basin had not yet developed. The stream-gradient index analysis for the Wierna River and associated wind gap 2 suggests that the ancient Wierna River had approached its base level of erosion, that is, it had largely recovered from that disturbance before uplift of the Mojotoro Range.

Uplift of the Mojotoro Range is loosely bracketed by the radiometric ages of 1.3 and 0.33 Ma, suggesting a time lapse of ~10^6 yr for full elevation. Considering the error in the ages themselves and the unknown time involved in folding and eroding the Oran Group strata before accumulation of the valley fill, the uncertainty on this estimate may exceed 30%. An incision of ~800 m yields a gross minimum estimate of 0.8 mm/yr for the rate of uplift, a moderate rate in a global comparison (cf. Burbank and Anderson, 2008, p. 160; Seong et al., 2008) but higher than the regional long-term average for the Eastern Cordillera in the Central Andes of 0.2–0.4 mm/yr (Gregory-Wodzicki, 2000; Mugnier et al., 2006). Although tectonic activity continues at present in the Lerma Valley region, it appears to be relatively weak over the Vaqueros and Mojotoro Ranges, judging from the low seismicity and apparent lack of deformation of the valley fill in the northern Lerma Valley. This condition would favor an approach to dynamic equilibrium for the northern streams. The stream-gradient index analysis for the Lesser-Vaqueros-Mojotoro River course (Fig. 11A) reveals that, despite local disequilibrium, a graded profile has developed, which agrees with tectonic quiescence.

Several tens of meters of Lerma Valley fill had accumulated before the Mojotoro-Castillejo uplift had broken ground: at the least a thickness equivalent to that of the Lesser River alluvial fan, ~70 m, and perhaps greater in the depocenter lows. After emergence, the Mojotoro-Castillejo uplift must have favored aggradation of the basin fill. The minimum aggraded thickness adjacent to the Mojotoro Range can be roughly estimated as the depth to the base of the Lake Lerma deposits, the oldest ascertaining the presence of a barrier to outflow. This depth was measured as 50 m in a seismic-reflection survey east of Cerrillos Hills (González Bonorino et al., 2003). Farther north,

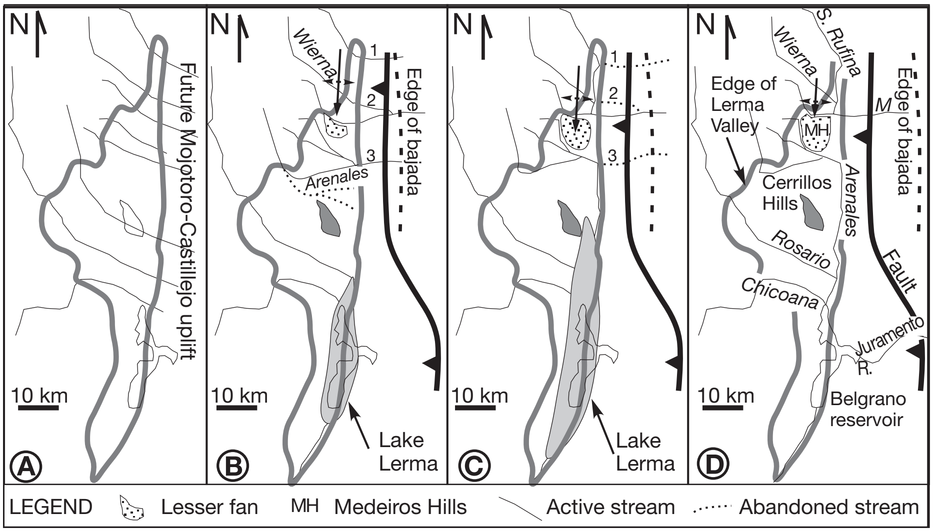

Figure 13. Plan-view evolution of the drainage in the late Pleistocene Lerma basin in response to emerging topography. (A) Early stage: Before emergence of topography, rivers flowed across the study area. The positions of the lower courses of the streams are hypothetical. (B) Intermediate stage 1: The Vaqueros and Cerrillos Hills anticlines have emerged, leading to entrenchment of the Wierna River and northward migration of the Arenales River. Also occurring is the incipient emergence of the Mojotoro Range and incision of future wind gaps. Numbers indicate wind gaps as in Figure 7B. Initial expansion of Lake Lerma. (C) Intermediate stage 2: The Santa Rufina and Wierna Rivers have been deflected southward and merged into the Caldera River, which joined the ancient Lesser-Vaqueros River to form the Mojotoro River. Maximum expansion of Lake Lerma. (D) Present-day stage for comparison. Thick gray line indicates boundary of the modern Lerma Valley; thick dashed line marks the foot of slope of the Mojotoro Range; thin dashed lines are abandoned channels; the thrust fault bounded the Lerma piggyback basin. M—Mojotoro River. Outlines of the Cerrillos Hills (filled after elevation) and the Belgrano reservoir are shown in all panels for geographic reference.

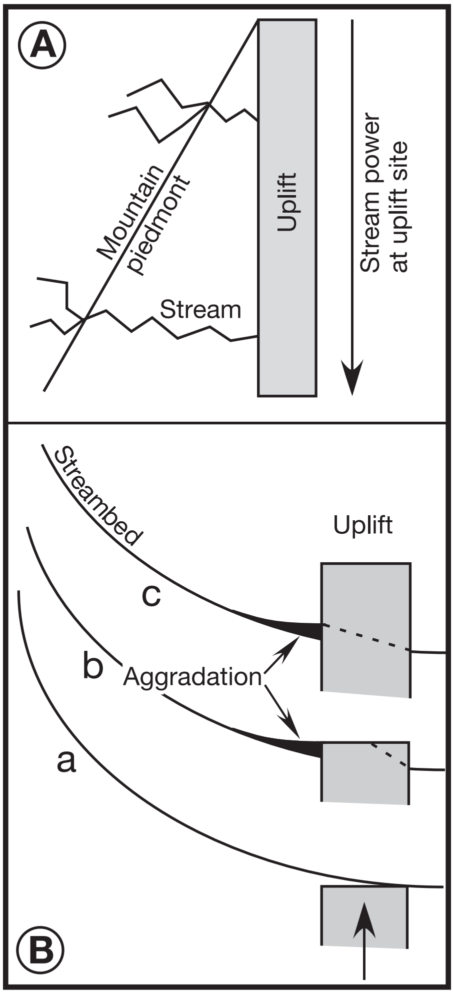

Figure 14. (A) Effect of diverging mountain-piedmont junction and axis of uplift on stream power available to incise into the rising bedrock. (B) A schematic of the cross-section evolution of the Lesser-Vaqueros-Mojotoro River. Stages represented decrease in age upward and show: (a) the pre-uplift situation, (b) initial uplift equaled by aggradation, and (c) further uplift detached from the basin fill. Figure is partly based on Humphrey and Konrad (2000) and Burbank and Anderson (2008, p. 194).

geoelectric surveys (Gutiérrez, 1995) show that the thickness of the fill beneath the channel of the Vaqueros River, probably related to an ancient terminal fan, increases to more than 50 m. Aggradation beneath the terminal alluvial fans of the Santa Rufina and Wierna Rivers may amount to 20–30 m (estimated from the difference in elevation between the observed and the computed profiles of the Wierna River, as shown in Fig. 12A). Starting with a graded profile before uplift, the amount of aggradation should represent the time it took the knickpoint to migrate backward across the rising, 10-km-wide Mojotoro uplift (Fig. 14B, stages a and b; cf. Humphrey and Konrad, 2000; Burbank and Anderson, 2008, p. 194). The channel remained active until aggradation rate lagged behind uplift rate in the Mojotoro Range (cf. Hilley and Strecker, 2005). Further uplift proceeded at a rate that approximately matched the downcutting rate of the Mojotoro River, the discharge of which had been strengthened by the input from the deflected streams to the north (Fig. 14B, stage c). Such balance accounts for the fact that rivers in the northern Lerma Valley incised hundreds of meters into the rising Mojotoro uplift but only a few meters into the valley fill.

CONCLUSIONS

Out-of-sequence contraction and uplift in the Eastern Cordillera during the late Pleistocene gave rise to the Vaqueros Range/Medeiros Hills and the Cerrillos Hills, followed shortly after by development of the Lerma piggyback basin and the Mojotoro-Castillejo Ranges. The succession in time of these events had not been previously established. The response of the Lerma Valley river system to emerging topography differed markedly north and south of the latitude of the City of Salta. In the north, the Santa Rufina, Wierna, and Lesser-Vaqueros-Mojotoro Rivers, favored by high rainfall amounts and steep channel gradients, initially carved antecedent channels through the rising Mojotoro Range. When defeated and diverted southward, summation of water discharges succeeded in maintaining open the Mojotoro water gap. The Vaqueros Range–Medeiros Hills uplift played a central role in the new drainage design by diverting the ancient Lesser-Vaqueros-Mojotoro River to an east-west course that captured southbound flows. Meanwhile, south of the present latitude of the City of Salta, once the Arenales River was defeated, all the water discharge fed Lake Lerma, which expanded until water level reached a pour point along structural lows, and carved a subsequent channel across the Castillejo Range. Defeat and diversion occurred when the Mojotoro Range had almost attained its present elevation, allowing the inference that it was caused by an orographically induced reduction in moisture influx to the Lerma basin.

The origin of the Medeiros strath terraces is shown to have been tectonic and related to uplift of the Vaqueros anticline. The evidence comes from treads tilted upstream and away from the contemporary active channel. The terraces were carved into deposits of a preexisting alluvial fan by rivers with gradients similar to those of nearby bedrock streams and steeper than that of the present-day aggraded Vaqueros River. The terraces represent times of approach to dynamic equilibrium punctuating protracted uplift during the final stage in the development of the Vaqueros anticline.

We reconstructed the ancient courses of the Santa Rufina and Wierna Rivers by reconnecting the active channels with their respective wind gaps. Stream-gradient index analyses on the restored stream channels suggest that, following disturbance due to the elevation of the Vaqueros Range, they had approached their base levels of erosion by the time the Mojotoro Range started to emerge. The Mojotoro uplift, in turn, altered the profile of the trunk Lesser-Vaqueros-Mojotoro River, which again approached its base level of erosion after a few tens of meters of sediment aggradation within the basin. The aggraded thickness was a fraction of total bedrock uplift, indicating that the basin fill was unrelated to the Mojotoro uplift. Subdued tectonic activity in the northern Lerma Valley and Mojotoro Range may reflect deceleration of bedrock uplift, a condition that would favor attainment of a graded profile by the Lesser-Vaqueros-Mojotoro River.

The setting of the Lerma piggyback basin in a thick-skin interior zone of the Andean fold-and-thrust belt brings forth the potential influence of inherited basement structures on basin morphology, for instance, in widening the low-gradient tract separating the mountain front and the rising forelandward margin of the basin. Out-of-sequence thrusting played an important role in the constitution of this broken foreland, and it may have been a consequence of earlier mild basement uplift in the distal foreland.

ACKNOWLEDGMENTS

This work was supported by Argentine government funds through projects PIP-CONICET 400-98 and PICT-REDES 1779. The ASTER 30 m digital elevation models were obtained from http://asterweb.jpl.nasa.gov/gdem.asp. ASTER GDEM is a product of the Ministry of Economy, Trade and Industry of Japan (METI) and the National Aeronautics and Space Administration. We thank Scott Miller (MIT) for a quite thorough and helpful review of an early draft of this paper. We also acknowledge the many pertinent and helpful criticisms and suggestions by referees and coeditor for the *GSA Bulletin*, Carlos Costa (San Luis University), Teresa Jordan (Cornell University), Greg Hoke (Syracuse University), and Eric Kirby (Pennsylvania State University). Helpful discussions with Ricardo Alonso (University of Salta) are acknowledged.

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Science Editor: Nancy Riggs
Associate Editor: Eric Kirby

Manuscript Received 26 July 2010
Revised Manuscript Received 25 February 2012
Manuscript Accepted 30 April 2012

Printed in the USA