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Neotectonics and Stream Piracy on the Lytle Creek Alluvial Fan, Southern California

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The Lytle Creek fan is the largest alluvial fan in the San Bernardino Valley, and one of the largest of such features in the coastal valleys of Southern California. It is, however, virtually a relict. The fan was formed in late Pleistocene time from debris carried down from the San Gabriel Mountains through a canyon etched out along the San Jacinto fault zone. The fan surface was subsequently incised by large, competent streams. Uplift along the San Jacinto fault resulted in development of deep trenches as down-cutting progressed. Alluvial terraces were developed in these trenches. Fault control of drainage, accompanied by further uplift and tilting, eventually led to complete beheading of the fan's drainage system. All flow to the fan was ultimately directed through the modern wash along the fan's eastern side. This wash follows the trace of the San Jacinto fault. Today, the Lytle Creek alluvial fan serves as an excellent example of the influential rôle that recent tectonic movements may play in an act of stream piracy.

This paper will examine the geomorphic evolution and demise of the Lytle Creek fan through analysis of the alluvial deposits and the landforms with which they are

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associated. Stratigraphy and pedogenesis of the alluvium tell much of the story, for here lies the evidence used for dating the geomorphic events sketched out on the following pages.

The Setting

Lytle Creek drains the southeastern end of the San Gabriel Mountains. These mountains lie in the central Transverse Ranges of Southern California (Figure 1). They are rugged, block-faulted, and thrust-faulted mountains consisting of a Tertiary to Precambrian intrusive and metamorphic basement complex that has been re-elevated by faulting during the Pleistocene epoch.[1] The diastrophism took place during the middle portion of the Pleistocene epoch. This is attested to by widespread folding of early Pleistocene and Pliocene sediments that outcrop along the southern flanks of the mountains. These deposits were subsequently overlain by relatively undeformed, later Pleistocene fanglomerates that have since become highly weathered themselves.[2] The fanglomerates comprise the "San Dimas Formation," and occur on a series of high-standing, heavily-dissected and truncated alluvial fan heads that form a narrow, discontinuous bench along the mountain front north of the Lytle Creek fan. The location of these fan remnants indicates the highest alluvial surface yet recognized in the San Bernardino Valley (Figure 2). Their surface (known as the "San Dimas" surface), lies more than ten meters above the Lytle Creek fan surface in the fan head and fan bay areas. It is clear that these deposits postdate the mid-Pleistocene uplift of the mountains.[3] The sediments had become deeply weathered and were mostly removed by erosion before the Lytle Creek fan was built.

Lytle Creek Canyon is a straight, narrow, V-shaped canyon cut into these mountains along controlling branches of the San Jacinto fault zone.[4] The area of its mountain drainage basin is approximately 124 square kilometers. The canyon's local relief is about 2,400 meters, from the fan bay to the highest portions of its divides. Lytle Creek

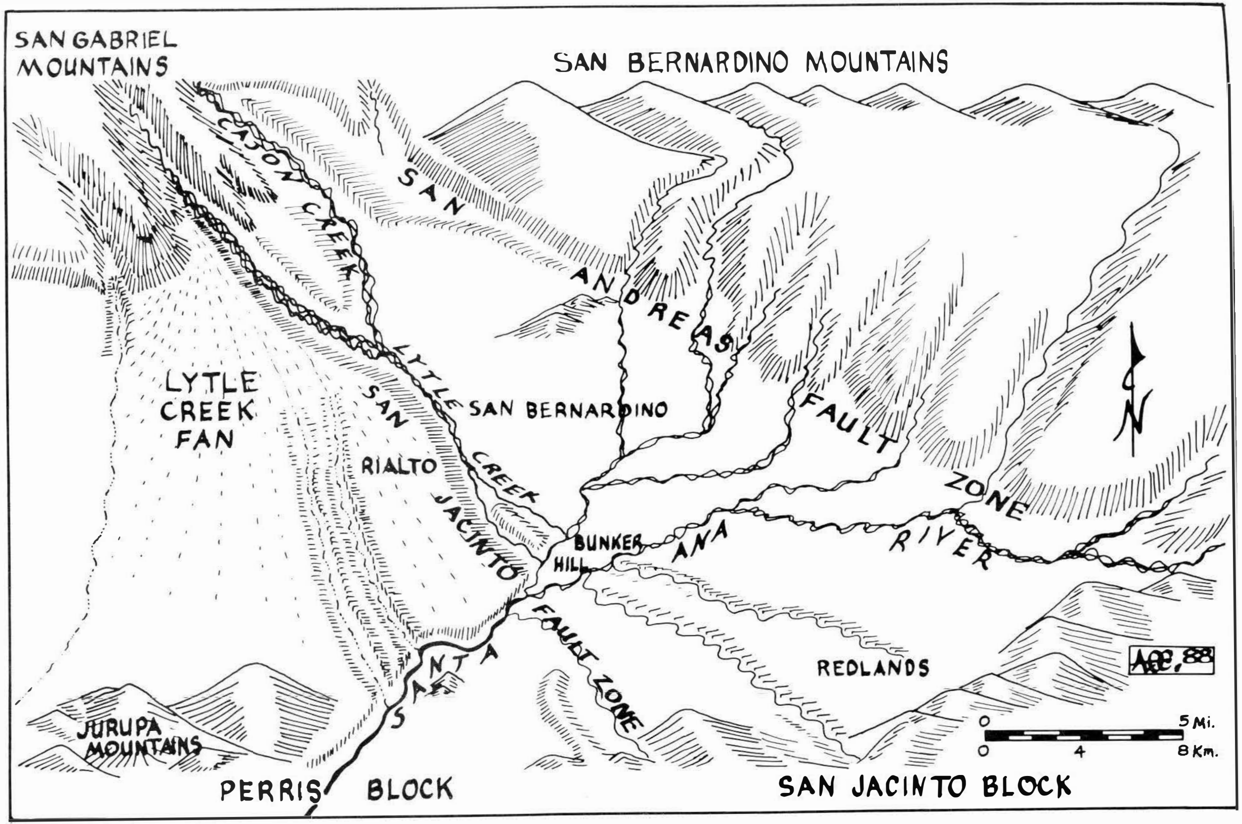

Figure 1. Major landforms and settlements of the San Bernardino Valley.

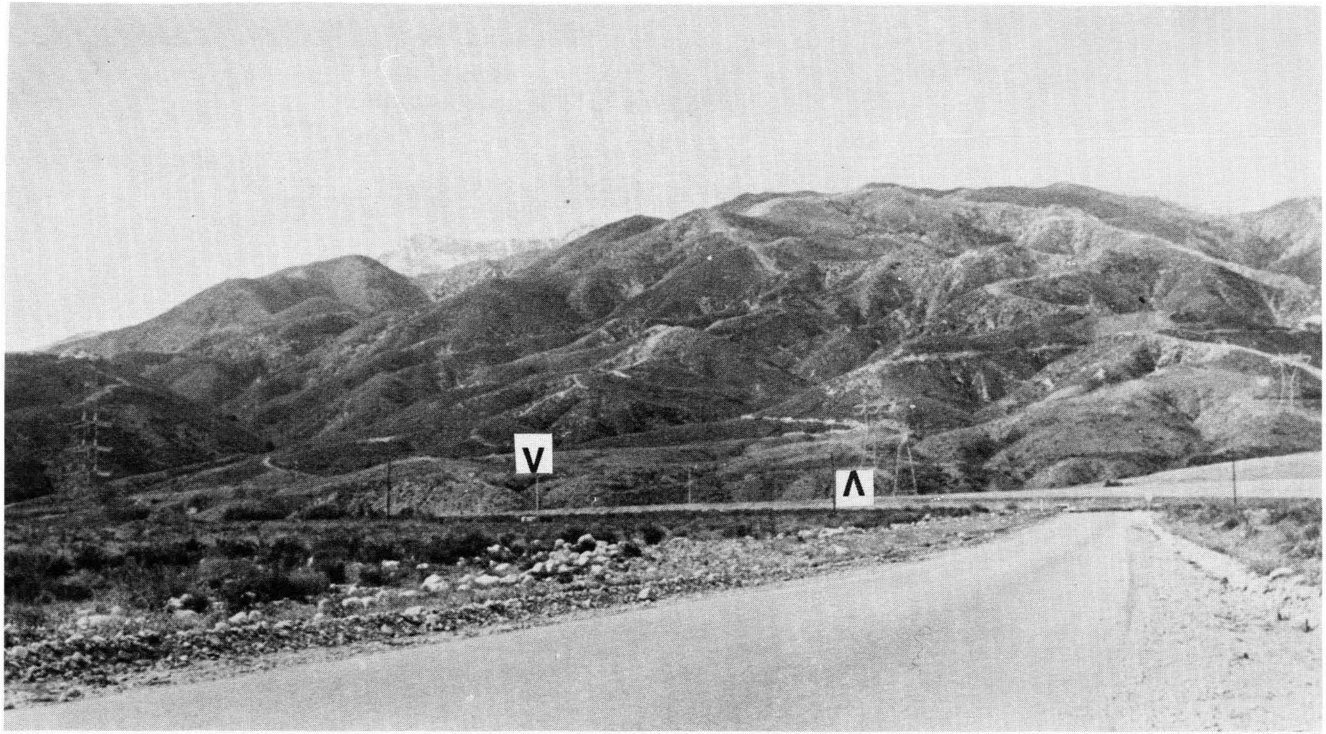

Figure 2. View looking northwest over the Lytle Creek alluvial fan north of Rialto. The eastern end of the San Gabriel Mountains are in the background. Lytle Creek Canyon is to the far right. The discontinuous high terrace along the mountain flank is produced by the truncated early fanglomerates. This is the highest (oldest) alluvial surface discernible in San Bernardino Valley. [Photo by author]

Canyon debouches into San Bernardino Valley along the northwestern portion of the valley's perimeter at an elevation of about 610 meters. Owing to a Mediterranean precipitation regime, Lytle Creek's discharge is quite irregular. The stream below the mountains is usually dry during the summer, and its winter discharge is highly variable.

Lytle Creek has built the largest alluvial fan in San Bernardino Valley. The fan extends in an arcuate pattern from the mouth of Lytle Creek Canyon southward over a distance of fifteen to twenty kilometers. Equally wide across its toe, the fan extends approximately the same distance east to west. To the west, the fan grades laterally into the bajada of the eastern San Gabriel Mountains. To the east, the fan is bounded by the modern course of Lytle Creek and the Cajon Creek fan beyond. To the southwest, the fan extends to the Jurupa Mountains—a low range of hills consisting largely of Mesozoic granitic rocks of the Southern California batholith which were intruded into Paleozoic metasediments.[5] To the southeast, the fan grades into terrace deposits of the Santa Ana River at an elevation of about 300 meters. The Santa Ana River drains San Bernardino Valley and flows westward to the Pacific Ocean about 100 kilometers away.

The modern course of Lytle Creek crosses San Bernardino Valley diagonally from northwest to southeast (Figure 3). The course is fairly straight and follows the San Jacinto fault zone to the point at which the stream enters the Santa Ana River. The San Jacinto fault is characterized by right-lateral strike-slip, rotational, and nearly vertical dip-slip displacements along its trace, which extends from the north side of the San Gabriel Mountains where it splays from the San Andrews fault, to below the western side of the Salton Sea, 200 kilometers to the southeast.[6] This fault separates two tectonic blocks in the local area south of the Transverse Ranges. These are the Perris Block west of the fault, and the San Jacinto Block to the east (Figure 1). The Lytle Creek fan lies on the Perris Block. Woodford, *et al*,[7] undertook an extensive study of the Plio-

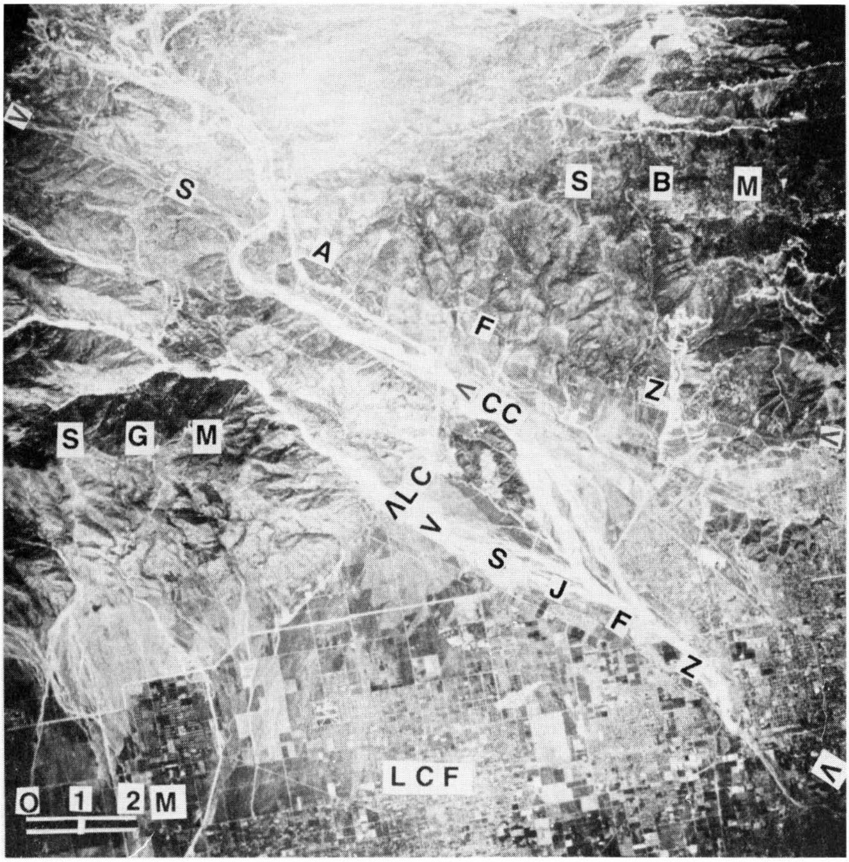

Figure 3. NASA Mission 164 high-altitude aerial photo, image number 3258. This image was taken from an altitude of approximately 10,000 meters in Spring of 1971. SBM, San Bernardino Mountains; SAFZ, San Andreas fault zone; SGM, San Gabriel Mountains; CC, Cajon Canyon; LC, Lytle Canyon; SJFZ, San Jacinto fault zone (and the modern channel of Lytle Creek); LCF, Lytle Creek fan. Scale is in miles. (M), North is at top.

Pleistocene history of the Perris Block and found evidence of repeated changes in local and general base level resulting in repeated episodes of rejuvenation.

Methodology

Empirical evidence used in this study was derived from a close examination of the alluvial stratigraphy, soils, and landforms of Lytle Creek fan. The various alluvial deposits and associated landforms shown on Figure 4 were all mapped on high-altitude, small-scale (1:120,000), black-and-white aerial photographs that were taken as part of National Aeronautic and Space Administration (NASA) Mission 164 in 1971 (Figure 3). Color and color-infrared (CIR) imagery of a similar scale was frequently consulted. That imagery was also provided by NASA Mis-

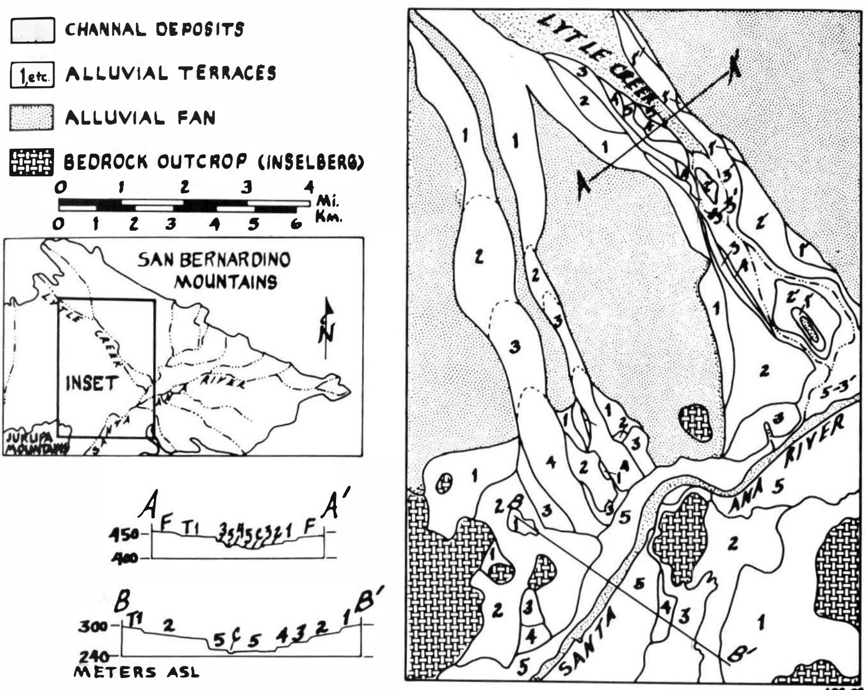

Figure 4. Geomorphic map of the Lytle Creek alluvial fan. Alluvial terraces are numbered from 1 and 1' (oldest) to 5 and 3' (youngest). The primed numbers indicate terraces east of the San Jacinto fault zone. The profiles are the same horizontal scale as the map, but vertically exaggerated by a factor of 20.

sion 164 and U-2 flights associated with NASA Mission 239, in 1973. The black-and-white panchromatic images exhibited good contrast and shadows, and for this reason they were useful in distinguishing landform boundaries. Color Ektachrome images allowed identification of varying soil types associated with different alluvial deposits, where soil color, degree of induration, and so forth vary with the age of the deposit. CIR imagery was most sensitive in depicting not only various types of rural land use, but also natural vegetation associated with the different surficial deposits and landforms. In addition, detailed field mapping of alluvial terraces was superimposed on low-altitude, conventional black-and-white, 23 cm. by 23 cm. air photos at a scale of 1:14,400, and also on USGS topographic quadrangles at a scale of 1:24,000 (San Bernardino North, 1954; San Bernardino South, 1954; Fontana, 1967; and Devore, 1966).

The stratigraphic correlation of these deposits is based upon similarity in clast lithology, Munsell color, coherence, soil development (including distinctive internal features, such as caliche and iron oxide staining), surface form, lateral continuity, stratigraphic position, altitude, and landform association.

Previous work on the geology of San Bernardino valley consists of several investigations: those of Mendenhall,[8] and Dutcher and Garrett,[9] are geohydrologic studies. A 1973 study by Elders, *et al*,[10] investigated the seismic character of the central valley area. Fife, *et al*,[11] and Morton[12] investigated hydrologic hazards. Clarke[13] mapped the surficial deposits and landforms of the entire valley. A detailed soil survey was completed by Woodruff and Brock in 1980.[14] Most recently, the San Bernardino Valley was mapped in its regional context by Bortugno and Spittler.[15]

Alluvial Stratigraphy

Over the centuries, Lytle Creek has laid down a thick section of alluvial materials. Repeated fluctuations in the stream's load, discharge, and channel position are documented by this sedimentary record. Through an examination of this stratigraphy, much of the stream's story can be told. Lytle Creek's alluvial deposits consist of immature, arkosic sands and gravels with occasional clayey or silty layers. There is great range in clast size, with boulders being common in the fan head. Clast size decreases downstream from the fan bay, while degrees of sorting and rounding gradually increase. The deposits exhibit numerous cut-and-fill structures, the result of shifting of the distributary channels across the fan surface.

Areas near the active channel and fan bay are frequently disturbed by periodic floods and by occasional flood control and channel maintenance work. In many cases, these areas are covered with a thin veneer of fresh gravels. In addition, the sediments in these areas may be locally truncated, ditched, and back-filled by such activity.

The great size of the Lytle Creek fan implies that the sedimentary pile was built up over a fairly substantial period of time. The volume of debris is certainly consistent with the size of Lytle Creek's mountain drainage basin, which encompasses an area of approximately 124 square kilometers. Since Lytle Creek's fan grades internally into other fans and bajadas on all sides south of the mountains, it is important to be able to distinguish that material deposited by Lytle Creek from alluvium contributed by other sources. Surface form provides some indication of this on the aerial photographs; however, the best evidence for provenance in the field comes from analysis of the petrology of individual clasts. Diagnostic clasts of the Lytle Creek alluvium are Pelona Schist (a distinctive dark blue-green, quartz-albite-sericite-schist), and quartz diorite.[16] The fan material is derived not only from Lytle Creek Canyon, but also from several adjacent smaller canyons. The Lytle Creek alluvium laps onto the northern flanks of the Jurupa Mountains and is easily distinguished from material derived from these hills. Debris from the Jurupa Mountains contains clasts of gabbro, tonalite, granodiorite, pegmatite, brucitic marble, and skarn[17]; and this material generally occurs as smaller clasts. Cajon sion 164 and U-2 flights associated with NASA Mission 239, in 1973. The black-and-white panchromatic images exhibited good contrast and shadows, and for this reason they were useful in distinguishing landform boundaries. Color Ektachrome images allowed identification of varying soil types associated with different alluvial deposits, where soil color, degree of induration, and so forth vary with the age of the deposit. CIR imagery was most sensitive in depicting not only various types of rural land use, but also natural vegetation associated with the different surficial deposits and landforms. In addition, detailed field mapping of alluvial terraces was superimposed on low-altitude, conventional black-and-white, 23 cm. by 23 cm. air photos at a scale of 1:14,400, and also on USGS topographic quadrangles at a scale of 1:24,000 (San Bernardino North, 1954; San Bernardino South, 1954; Fontana, 1967; and Devore, 1966).

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Creek, the next large stream east of Lytle Creek, has produced an alluvial fan adjacent to and east of the Lytle Creek fan. Material in this fan was derived from the Cajon Pass area and contains many clasts of the Pelona Schist. Amphibolite, graphite, and marble from Lone Pine Canyon, a mountain tributary of Cajon Creek, are also present in Cajon Creek fan, but not in the Lytle Creek fan above Cajon Creek. Cajon Creek joins Lytle Creek about five kilometers south of the mountains in Lytle Creek wash. The petrology of adjacent sediment sources west of Lytle Creek is so similar that surface form must be relied upon for discrimination. Here, the pattern of contours on the 1:24,000 topographic quadrangles is useful in determining the approximate location of the western boundary of Lytle Creek fan.

Lytle Creek and the Santa Ana River have produced well-developed sequences of alluvial terraces along the eastern and southern margins of the Lytle Creek fan (Figure 5). A soil toposequence has developed on the fan and on terraces along Lytle Creek and the Santa Ana River. Weathering and soil formation vary with relative age of the terraces. This provides evidence that is not only useful in correlating the alluvial deposits, but also, and more importantly, helps to unravel the alluvial history of the Lytle Creek fan.

Soils on the Lytle creek fan are best developed on the highest interfluves and highest terraces west of the wash, away from the fan head. These mature soils are confined to a few localized areas: Grand Terrace south of the Santa Ana River opposite the Lytle Creek confluence, Green Acres south of Rialto, and El Rancho Verde north of Rialto are the main localities. These localities all occur west of the San Jacinto fault, on uppermost surfaces where broad, flat exposures of well-drained, sandy fluvial material are found. In places, the material is so massive and coherent that it stands in a high, nearly vertical slope (Figure 6). Coherence is due both to compaction and calcite cementation. In some cases, beds and stringers of caliche may be present. The Cox horizon colors the slope

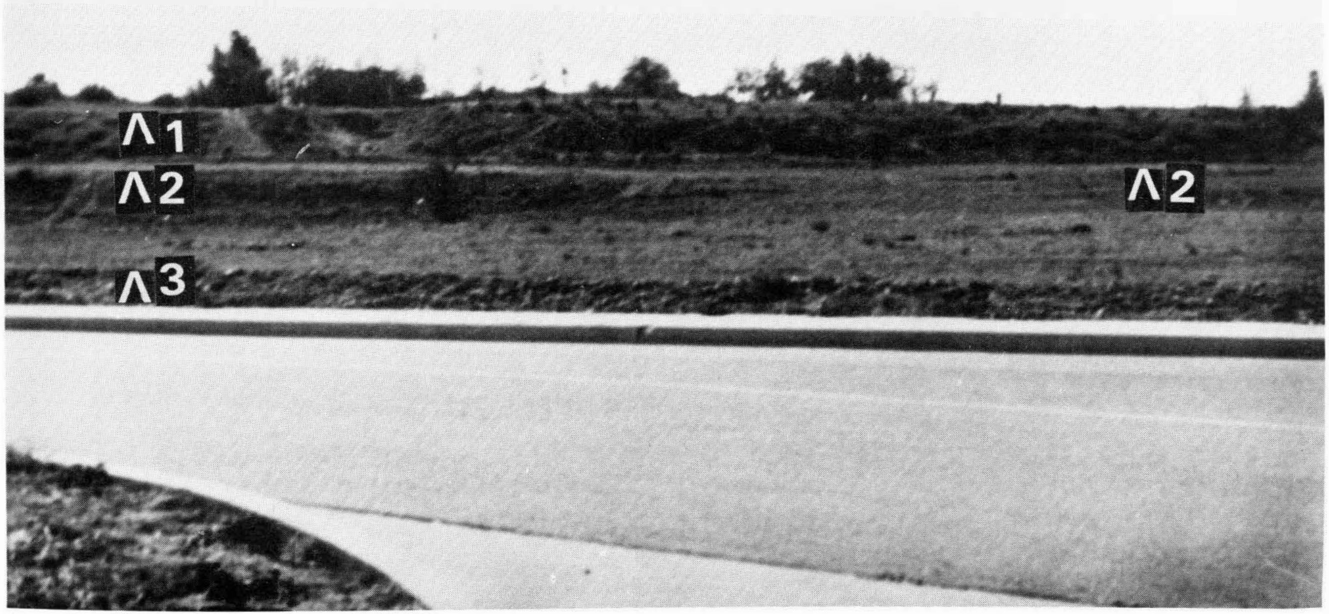

Figure 5. Alluvial terrace sequence west of the San Jacinto fault zone. This shot was taken in North Rialto (Frisbee Park), just west of the easternmost channel of Lytle Creek. Terrace surfaces 1, 2, and 3 are visible in the photo. Terraces 4 and 5 are behind the photographer. [Photo by author]

Figure 6. High alluvial fan and terrace sequence at Green Acres south of Rialto. This photo illustrates the terraces between the modern and relict channels of Lytle Creek near the southern end of the alluvial fan. The view is looking west. The relict fan surface is marked "F." Note the darker color (red) and degree of consolidation of the older alluvium. Terrace surfaces 1, 2, and 3 are visible. Terraces 4 and 5 are behind the photographer. [Photo by author]

and accentuates it. The unweathered Cn horizon may be protected to considerable depth by this cap. Soils on these high, old surfaces are Brown Soils belonging to the Alfisol order, Xeralf suborder. The soils are Typic Haploxeralfs of the Greenfield series.[18] They show a mature profile, including an illuvial and oxic B horizon. The A horizon is a sandy, cobbly loam, to about thirty centimeters in thickness, brown (10YR 5/3) in color, with a granular structure. Root casts, root channels, and some carbonaceous material occur in the horizon. The B horizon extends down to about 150 centimeters. It is redder in color (7.5YR 6/3), may locally contain diffuse accumulations of caliche ($CaCO_3$), shows evidence of illuviation by being slightly plastic owing to clay content, and possesses a blocky structure with clay skins. The Cox horizon is reddish-brown in color (5YR 5/3), and rapidly grades into the Cn horizon of unaltered alluvium at a depth of two to three meters below the surface. The presence of clay and iron oxides indicates some antiquity consistent with a late Pleistocene age and the more humid climate associated with those times. Dutcher and Garret,[19] Morton,[20] and Bortugno and Spittler,[21] have mapped the deposits in these localities as "older alluvium."

Lower terraces have immature soils of the Entisol order, mostly Typic Xeropsamments and Xerofluvents. These are generally marked by an (A) C profile. The (A) horizon is cobbly, sandy loam, from fifteen to thirty centimeters in thickness, brown in color (10YR 4/3), possesses a granular structure, and is non-plastic. The C horizon extends down to about 150 centimeters, is lighter brown (10YR 6/3) in color, and possesses a slightly harder and more massive structure. A large sample of wood was recovered from a terrace deposit of intermediate level within the San Jacinto fault zone at the mouth of the concrete Lytle Creek flood control channel during a State Department of Water Resources investigation in 1971, and was dated by the radiocarbon method at 33,000± 900 years B.P.[22] This indicates that the Lytle Creek fan was present and had been trenched prior to the middle of the Wisconsin age. The 33,000 year age falls between the Tenaya stadial of 45,000 years B.P. and the Tioga stadial of 20,000 years B.P.[23] The date also indicates that channel alluviation which led to the deposition of these terrace materials was in progress 33,000 years ago, and thus provides evidence for an interval of interstadial aggradation.

The thickness of the (A) horizon of terrace soils decreases with decreasing terrace height. Material on the lowest terrace is virtually indistinguishable from modern channel deposits, save for the presence of small amounts of undecomposed organic material—plant fragments, derived from living vegetation rooted in the sandy gravels. Carbonaceous material from sag pond sediments associated with alluvial gravels in the low terrace on the east bank of Lytle Creek, north of the San Ana River and east of the San Jacinto fault, yielded a radiocarbon date of 5,540± 200 years B.P.[24] This date indicates a Holocene age for the low terrace and the wash. However, the date for the sag pond sediments can only serve to determine a minimum age for the surrounding terrace. A study of the alluvial sequence in nearby Cajon Canyon has ascribed a very late Pleistocene and Holocene age for sediments in that nearby area.[25]

Trenching, Terrace Development, and San Jacinto Fault

The San Jacinto fault has had a profound influence on the geomorphic development of both the Lytle Creek alluvial fan and modern Lytle Creek itself. Indeed, the significance of this fault has been so great that the history of the fan and fault are intimately intertwined. The San Jacinto fault nearly parallels, and in some cases closely coincides with, the west wall of the modern Lytle Creek wash. Vertical displacements along the fault have resulted in the production of two separate sequences of alluvial terraces on either side of the fault. The highest terrace sequence contains the most terraces. This occurs on the west side. Here, as many as five terraces can be seen between the floors of the washes of Lytle Creek and the Santa Ana River, and the fan's high interfluves. Extensive terraces are also found in two large ancestral channels on the Lytle Creek fan to the west of the modern channel (Figure 4). Terrace surfaces are more or less continuous from one channel to the next west of the fault. The highest terrace grades into the alluvial fan surface. A slight rise marks the boundary between the uppermost terrace and a slightly higher fan interfluve. The lowest terrace surface is immediately adjacent to the active wash and, at most, several meters above its sandy floor. In some instances, intermediate terraces have been removed by the stream's lateral cutting.

A simpler, lower, broader sequence of alluvial terraces occurs on the Cajon Creek fan east of the modern Lytle Creek wash. This sequence contains three alluvial terraces and is developed on the east side of the San Jacinto fault. Like its counterpart in the west, the highest terrace grades back into the fan surface, while the lowest terrace sets just above the floor of the wash. Between the two fans, Lytle Creek wash varies in width from about one-half a kilometer to more than two kilometers. Small terraced islands exist in the wash (Figure 7).

The highest terrace in the western sequence is as much as twelve meters above its eastern counterpart in the central part of the valley. This relationship is shown by profile A-A' (Figure 4), which is at right angles to the thalweg. In the fan head area, vertical displacements along the San Jacinto fault are virtually zero; offset increases southward, however. The west side of the fault is more than twelve meters above the east side in the central part of the valley, and this discordance increases to more than thirty meters at the southern extremity of the fan. Near the Santa Ana River, the highest terrace surface in the western sequence (Grand Terrace) is more than sixty meters above the thalweg, while the uppermost terrace to the east exhibits less than thirty meters of height. This southward-increasing vertical offset is evidence of rotational slip along the fault, with the Perris Block rotating up to the south relative to the San Jacinto Block. The hinge of rotation appears to be in the fan head area. This

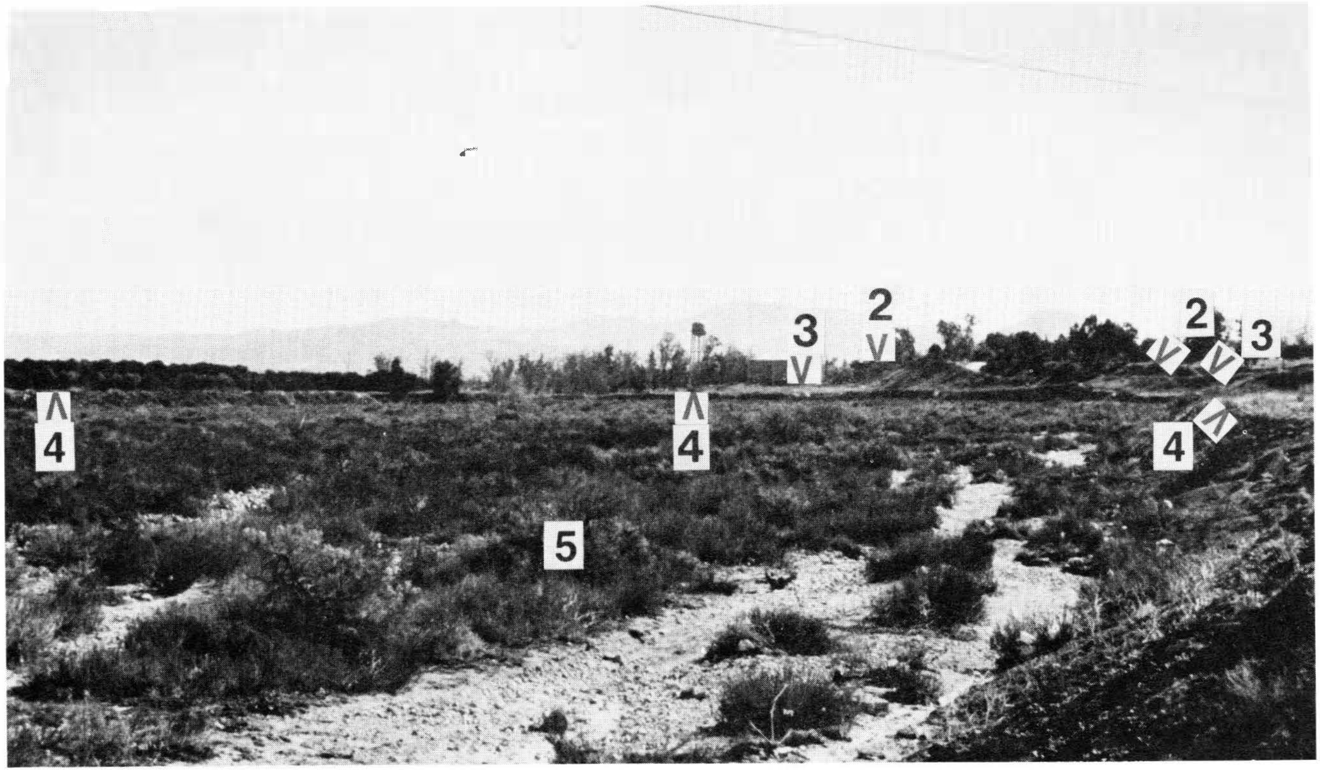

Figure 7. Alluvial terrace sequence east of the location shown in Figure 5. Terrace surfaces 2, 3, 4, and 5 are visible from this point. Note the "terrace island" to the left. The modern channel is east (left) of the island; its floor is cut well below surface 5, shown in the foreground. The view is looking south-east. [Photo by author]

is also evidenced by the lowering of terrace risers upstream on the Lytle Creek fan, until the surfaces eventually feather into one another near the fan head.

The Lytle Creek fan has been incised along several of its distributary channels. Down-cutting was maximum near the toe of the fan where the channels join that of the Santa Ana River. This down-cutting was terminated upstream by headward erosion to produce the mid-fan trenches. Deep trenching also occurred on the fans and bajada further west.[26] The Cajon fan to the east was also incised; but the large, deep, well-developed channels typical of the Lytle Creek fan were not produced there.

As a result of this incision, three major channels occur on the Lytle Creek fan. These consist of (1) an eastern channel, which follows the trace of the San Jacinto fault and runs in a virtually straight line along the eastern edge of the fan, from the mouth of Lytle Creek Canyon to the confluence with the Santa Ana River (Figure 8), and (2) two western channels, which run nearly parallel to each other near the central axis of the fan. Apparently, all three channels were simultaneously active for some time, as each contains a sequence of terraces which can be traced laterally to the others and to those along this section of the Santa Ana River.

Tectonic activity also led to a minor drainage disruption near Lytle Creek's mouth. Buckling of older alluvium in the fault zone in the southern part of the valley raised a horst-like ridge, known locally as "Bunker Hill Dike."[27] This ridge rises to a height of more than six meters over a distance of about one kilometer.[28] Its presence causes the eastern channel to split and flow along either side of the structure in separate streams which join the Santa Ana River at separate inlets a short distance to the south (Figure 4).

Geomorphic History and Conclusions

The stratigraphic and geomorphic data discussed above may now be integrated to allow a synthesis of the historical development of lower Lytle Creek and its alluvial

Figure 8. Oblique air photo looking northwest over the Lytle Creek alluvial fan from an altitude of about 3,000 meters. The easternmost channel now carries all the flow that was once directed over the fan. The course of this channel follows the San Jacinto fault zone as marked in the photo. [Photo by Chris Clarke]

fan. Data from available dates, weathering, and soils, as well as geomorphic and stratigraphic relationships indicate that the Lytle Creek fan developed during the latter part of the Pleistocene epoch. At some time, prior to 33,000 years ago, uplift of the Perris Block along the San Jacinto fault produced incision along distributary channels of the Lytle Creek fan. These channels carried mountain runoff across the valley floor and into the Santa Ana River. Down-cutting was concentrated in three large master channels, which became deep, mid-fan trenches.

The magnitude of the Lytle Creek trenches is a result of two factors. First, uplift of the lower and mid-fan areas was generated by rotational displacements along the San Jacinto fault; and because this uplift was greatest at the toe, deepening was maximum there. Second, the relatively large drainage area of Lytle Creek Canyon is capable of producing a large competent discharge; and this flow has been capable of significant erosion.

The dominance which the mid-fan trenches attained as loci for water transport resulted in general deactivation of Lytle creek's fan surface. Later aggradation/degradation cycles led to the development of alluvial terraces in these trenches. The Santa Ana River acted as local base level for streams flowing through these trenches, as evidenced by the homotaxial nature of the Lytle Creek and Santa Ana River terraces.

The three terraces east of the San Jacinto fault and below the San Dimas surface indicate three phases of alluviation: (1) the early fan building phase, (2) a second phase occurring in entrenched channels around 33,000 years ago, and (3) a mid-Holocene phase of channel alluviation around 5,500 years ago. Additional surfaces west of the fault are the result of a combination of tectonic uplift coupled with lateral stream cutting.

Eventually, upward displacement of the alluvial fan and incision along the fault trace led to a complete diversion of the Lytle Creek drainage into the eastern-most channel. This act of stream piracy left the Lytle Creek alluvial fan "high and dry." Beheading of the fan must have happened late in its history, because four of the five alluvial terraces present in the eastern channel can be traced laterally along the Santa Ana River and into the lower parts of the two western channels. The fifth, or lower-most terrace, is missing in these two channels, which are now abandoned. If this terrace roughly correlates with the low terrace east of the San Jacinto fault, which has a minimum date of 5,500 years B.P., then the tectonically-induced piracy of the headwaters of the alluvial fan must have been completed by mid-Holocene time. It has been a relict feature subject to minor dissection from surface runoff ever since. Today, the Lytle Creek alluvial fan serves as an excellent example of the influential rôle that recent tectonic movements may play in an act of stream piracy. The Lytle Creek morphogenetic system is dynamic, not static. Tectonic events have had a significant impact on the alluvial history. Periodic alluviation, uplift, and erosion have created a palimpsest on the landscape. Only by mutual examination of sedimentary, pedogenic, and erosional evidence can the true, polygenetic character of the landforms be ascertained. The events discussed in this paper have given Lytle Creek its own unique character; yet, enough remains that is generally applicable to permit the Lytle Creek fan to serve as a paradigm for the study of alluvial fans in tectonically active regions elsewhere.

NOTES

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