Ephemeral stream response to growing folds

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ABSTRACT

The response of ephemeral alluvial streams to active tectonics is not as well established as those documented for perennial alluvial streams. This study documents the response of ephemeral streams transverse to growing folds along the north flank of the San Bernardino Mountains in southern California. The growing folds emerge amid a broad, sloping piedmont mantled by north-dipping alluvial fans and underlain by coarse, angular gravel and sand of mixed provenance. The study area contains fans composed of two distinct lithologies that control the expression of the folds. Sediment transport processes differ among alluvial perennial and ephemeral channels and play a primary role in defining the range of responses that ephemeral streams have to an actively rising fold. We find that ephemeral streams respond by (1) changing pattern from a single, slightly incised channel with well-defined banks to a braided channel upstream of the fold axis, (2) incising across the fold axis, preserving a terrace and braid bars, and (3) returning to a single-thread, less incised channel downstream of the fold axis. This channel response is documented for both a topographically obvious anticlinal fold, the Cougar Buttes anticline, as well as a suspected, but not topographically obvious anticline, the Pitzer Buttes anticline. Variations from this general model appear to be correlated with locations of slow fold growth and/or channel alluvium that is fine grained and of low cohesion. A growing fold, such as the Cougar Buttes anticline, provides a laboratory for the investigation of the development of transverse streams with respect to position along strike with the fold axis. Some streams crossing the Cougar Buttes anticline are antecedent, whereas others are consequent to the growth of the fold.

These observations lay the foundation for a conceptual model for ephemeral stream response to active tectonics, particularly useful in identifying previously unrecognized actively rising folds. In this study, the fold axis of the Cougar Buttes anticline is revealed to extend at least 1 km beyond its current obvious topographic expression. Because ephemeral streams are sensitive to tectonic deformation, they can be used locally in paleoseismological investigations, regionally to understand the strain partitioning between the Big Bear and Mojave blocks, and conceptually to constrain geodynamic models investigating the interaction between surface processes and the geometry of and slip rates on faults responsible for fold growth.

Keywords: California, San Bernardino Mountains, ephemeral streams, channel geometry, alluvial fans, active tectonics.

INTRODUCTION

Blind thrust faults occur in many compressional tectonic settings, and they are capable of generating large damaging earthquakes, such as the 1994 moment magnitude ($M_w$) 6.7 Northridge and the 1987 local magnitude ($M_L$) 5.9 Whittier Narrows earthquakes. Sometimes these faults have no substantial historic seismicity and no obvious geomorphic expression, so their relative activity and associated seismic hazards are poorly known. In southern California, previous studies have focused on the active uplift and geomorphic response to growing folds (Bullard and Lettis, 1993; Burbank and Verges, 1994; Keller et al., 2000; Azor et al., 2002; Bielecki and Mueller, 2002) including the Wheeler Ridge anticline (Mueller and Suppe, 1997; Mueller and Talling, 1997; Keller et al., 1998). These studies have led to emerging ideas on how mostly large (basin areas greater than 10 km$^2$) transverse channels respond to fault geometry and rates of slip on faults responsible for fold growth (van der Beek et al., 2002). Given an existing appreciation for the response of perennial alluvial rivers to active tectonics (Ouchi, 1985; Schumm et al., 1987; Harbor, 1998; Schumm et al., 2000) as well as the overall landscape response to growing folds, we investigate the specific behavior of small, strictly ephemeral alluvial streams to growing folds on a tectonically active mountain front piedmont in southern California.

Active tectonics influences the overall valley gradient of alluvial channels. In perennial meandering streams, this change in gradient typically elicits a response through an adjustment of channel morphology and/or sinuosity (Ouchi, 1985) or in perennial braided streams through the number of braid bars (Germanoski and Schumm, 1993). In contrast, the response of ephemeral alluvial streams to active tectonics is not as well documented. The processes and characteristics of ephemeral streams in arid settings differ from perennial streams in several ways. Most notably, ephemeral streams host both fluvial and debris-flow processes (Bull, 1997). Differences in how sediment is transported in ephemeral versus perennial streams should be reflected in different responses to similar tectonic deformation.

Upward of ~30% of the world’s active compressional tectonic settings lie in arid and semi-arid lands (Moore and Twiss, 1995), and geomorphic analysis has grown to be a primary means of assessing the seismic-hazard potential, growth, and activity of folds and structures...
within these settings (e.g., Bullard and Lettis, 1993; Keller et al., 1998, 1999, 2000). The dynamic interaction between surficial and tectonic processes has been used to alternately argue for a dominantly structural control on drainage development (Boudiaf et al., 1998; Hovius et al., 1998, 1999, 2000) or for dominant surficial process control on evolving structures (Mus-suridis et al., 1992; Tucker and Slingerland, 1994, 1996; Pavlis et al., 1996; Delcaillau et al., 1998). If important insights into convergent tectonic processes are to be made using geomorphic techniques, then it is clear that specific ephemeral stream-tectonic interactions must be defined and characterized.

This paper presents the results of a field study conducted along the north flank of the San Bernardino Mountains of southern California, near the town of Lucerne Valley (Fig. 1). The results document how ephemeral streams interact with growing anticlines thought to have a relatively simple fault-propagation fold geometry in an arid landscape. The underlying premise in this study is that ephemeral streams should have a quantifiable, measurable response to subtle or large changes in longitudinal gradient imposed by actively rising structures. First, we document such a response in an area where the topography clearly indicates the location of an actively growing fold. Using these results, we are then able to recognize similar actively growing folds in adjacent areas where the topographic expression of such a fold is equivocal or absent. Ephemeral streams have been described primarily in qualitative terms (Bull, 1991, 1997); this research seeks to characterize ephemeral streams quantitatively in the context of active tectonics, and thus, helping to fill a major gap in the understanding of these fluvial systems.

The paper discusses the specific suite of field methods necessitated by this particular setting, presents quantitative and qualitative data on channel metrics, delimits the range of channel behaviors in this setting, explores some conceptual models for the development of transverse drainages, and draws some insights into fault-and-fold behavior in this specific convergent setting. This study presents a framework for understanding the response of ephemeral streams as they traverse active uplifts and for comparing ephemeral and perennial stream response to active tectonics. This framework provides a tool to better evaluate the seismic hazards in Lucerne Valley, because the fluvial system has compelled us to consider fault strike lengths longer than those previously mapped.

**GEOLOGIC AND TECTONIC SETTING**

Southern California tectonics are dominated by the right-lateral San Andreas fault. As the San Andreas fault steps through its “big bend” from south of Los Angeles to Santa Barbara, a broad band of transpression forms, across which the Transverse Ranges are rising (Fig. 1). North of the Transverse Ranges and bound on the northwest by the left-lateral Garlock fault is a relatively rigid crustal block called the Mojave block. Northwest-trending right-lateral strike-slip faults synthetic to the San Andreas strike...
through the block and are estimated to accommodate between 9 and 23% of the relative motion between the Pacific and North American plates (Southern California Earthquake Center, 2001). Some of these northwest-trending faults are seismically active, as demonstrated by the 2001 Landers earthquake that ruptured portions of the Johnson Valley, Landers, Camp Rock, and Homestead Valley faults (Fig. 1). The north flank of the San Bernardino Mountains marks a complex transition between the northward-driven shortening of the Transverse Ranges and the right-lateral strike-slip offset across northwest-striking faults in the Mojave block (Fig. 1).

The study area is located in the piedmont of the north flank of the San Bernardino Mountains. The piedmont is dry, receiving on average only 13 cm of precipitation per year, with the majority received during the winter months as low-intensity frontal storms. Data come from a 10-km-wide area extending from the western limit of Lucerne Valley to the eastern edge of the Blackhawk landslide (Fig. 2). Elevation varies from 914 m (3000 ft) in the Mojave block in the north to 1372 m (4500 ft) at the San Bernardino mountain front in the south. A series of east-striking anticlines and fault scarps mark the location of major structures in the piedmont (Eppes et al., 2002). A regional record of seismicity, trench studies, and paleoseismic analyses (Spotila and Anderson, 2000) suggests that these structures are tectonically active.

The San Bernardino Mountains were uplifted in two distinct phases (Meisling and Weldon, 1989), with each phase having a significant impact on the stratigraphic units in the foreland that are now being uplifted and folded. The first phase of uplift began in the late Miocene to early Pliocene (between 9.5 and 4.1 Ma) as crystalline rocks of the ancestral San Bernardino Mountains were thrust southward along the Squaw Peak thrust system. Predating and concurrent with the first phase of uplift, the regional drainage system flowed from north to south, draining the Mojave block directly across what is now the San Bernardino Mountains. Poorly consolidated continental redbed siltstones and sandstones of the Old Woman Springs Formation were deposited across the study area during the Miocene and Pliocene by these south-flowing drainages (Meisling and Weldon, 1989). Scattered clasts of Mojave block provenance basalt deposited in the Old Woman Springs Formation attest to the northern provenance of these sediments. Portions of the Old Woman Springs Formation have subsequently been reworked into younger alluvial fan deposits, as demonstrated by the presence of basalt clasts in the fan deposits. The main portion of the modern San Bernardino Mountains, the Big Bear block, was uplifted during the late Pliocene and early Pleistocene (between 2.0 and 1.5 Ma) along the North Frontal Thrust System (NFTS). This thrust system is comprised of a series of south-dipping reverse faults that bound the north flank of the San Bernardino Mountains and form an ~70-km-long escarpment. The new phase of thrusting resulted in the reversal of the Old Woman Springs Formation drainage and the initiation of northward-directed deposition of the Cusherbury Springs Formation, an early Pleistocene, gray and tan coarse fanglomerate and sandstone (Shreve, 1968; Meisling and Weldon, 1989). Middle and late Pleistocene alluvial fans (Miller et al., 1998; Powell et al., 2000; Miller et al., 2001) that mantle the modern piedmont are texturally distinct from and disconformably overlie the Cusherbury Springs Formation. Fan deposits grain sizes tend to become finer downstream, and interfinger with fine-grained eolian and lacustrine sediment in the center of the Lucerne Valley (Fig. 2).

The Helendale fault, a northwest-trending right-lateral fault of the Mojave block, intersects the NFTS at approximately a 45° angle and strikes through the eastern portion of the Lucerne Valley (Fig. 2). Although published geologic maps show the Helendale fault intersecting the NFTS, the cross-cutting and relative activity relationships are unclear (Bryan and Rockwell, 1995; Spotila and Sieh, 2000). East of the Helendale fault, the mountain front is composed primarily of Precambrian to Paleozoic limestones and marbles that are exposed as roof pendants to Mesozoic plutons. West of the Helendale fault, the mountain front is composed primarily of Mesozoic granite. This lithologic change across the Helendale fault results in alluvial fans of distinctly different parent material (Fig. 2). We will demonstrate that this difference in parent material controls the expression of folding, source material for ephemeral channels, and magnitude of channel pattern change observed.

Contemporary uplift of the San Bernardino Mountains is indicated by late Pleistocene and possibly Holocene fault scarps along the

Figure 2. Shaded relief map of the Lucerne Valley and northern flank of the San Bernardino Mountains. See Figure 1 for location. The North Frontal Thrust System (NFTS), the Helendale fault, and younger thrust faults and anticlinal structures are indicated. Notice that piedmont alluvial fans are composed primarily of limestone east of the Helendale fault and granite west of the Helendale fault. Detailed topography and geology of the Cougar Buttes anticline and the Pitzer Buttes anticline are mapped in Figures 3, 4, 9, and 10 (inset).
piedmont (Spotila and Anderson, 2000; Eppes et al., 2002). The deformation front has propagated northward, away from the NFTS as a complex zone of blind or recently emergent south-dipping thrust faults. North-vergent thrust faults emerge in the core of folds, forming a fault-propagation geometry in the medial piedmont. Here the San Bernardino granitic bedrock, Old Woman Springs Formation, Cushenbury Springs Formation, and Pleistocene alluvial fans are folded into anticinal ridges. The topographic expression of these anticlines is linked to soil development on the alluvial fan surface (Eppes et al., 1998, 2002) where carbonate parent materials foster resistant carbonate-cemented soils (petrocalcic horizons) that support high-standing, steep fold limbs. For example, fans with a limestone provenance west of the Helendale fault lack a similar, thick petrocalcic horizon. The low infiltration capacity of clay-rich soils and the easy erodibility of these granitic sediments result in greater erosion and modification of the fold limbs throughout the fold growth process. As a result, topographic anticlines are not obvious on the granite piedmont even though mapping of deformed strata clearly marks their presence.

Incision through the piedmont anticlines by transverse drainages has allowed tributary strike drainages to breach their cores, exposing the softer, underlying Cushenbury Springs and Old Woman Springs Formations. The most distal of these anticlines, the Cougar Buttes anticline, represents a late Quaternary expression of shortening across the San Bernardino Mountains (Fig. 2). The Cougar Buttes anticline (Fig. 3) extends across the limestone alluvial fans as a distinct topographic ridge for ~2 km. The fold has an amplitude of 20 m at its center that decreases to 12 m measured in the last transverse valleys along strike to the east and west. Fold width varies from 160 to 200 m. The fold core exposes a north-verging thrust fault with dips to the south ranging from 19° to 25°. The fold is odd in the sense that the dips on the backlimb range from 20° up to 55°, whereas dips on the forelimb range from 2° to 26°, with steeper dips generally near the center of the fold (Fig. 3). Both limbs are capped and supported by a resistant 2–3-m-thick petrocalcic horizon. The inferred trace of the thrust fault in the core of this fold is concave toward the foreland, an observation also at odds with a north-verging structure. The Old Woman Springs and Cushenbury Springs Formations are exposed in the core of the fold. The petrocalcic horizon forms a well-defined stratigraphic marker bed that allows direct observation of fault offset. The fold axis has been cut by several transverse ephemeral streams that have incised valleys 12–20 m deep. The watersheds feeding these transverse channels range in area from <1–10 km² and either head on the alluvial fan itself or on the mountain front. A photo cross section of the valley carved through the fold by Middle wash shows the stratigraphy, the fault plane, and the 15 m of relief that exist between the crest of the fold and the channel bottom (Fig. 3).

**FLUVIAL EXPRESSION OF ACTIVE TECTONICS**

Perennial alluvial streams mutually adjust their dimensions, shape, pattern, and gradient in response to external factors such as climate, tectonics, or sediment supply (Leopold and Maddock, 1953). The perennial alluvial channel has bed and banks composed of the material transported by the river under prevailing flow conditions (Schumm et al., 1987). As discharge increases downstream, the depth of the channel increases and the gradient of the stream decreases, both proportionally to discharge and grain size fining (Leopold and Maddock, 1953). In contrast to perennial streams, the depth of ephemeral stream channels in semi-arid regions tends to increase less rapidly and gradient tends to decrease less rapidly in the downstream direction, both due to high water loss and increase in suspended sediment concentration in the downstream direction (Schumm et al., 1987).

Here our usage of the term “ephemeral channel” does not imply a channel that is only seasonally present; rather, it refers directly to the channel of a stream where the flows are infrequent. Additionally, ephemeral streams in arid regions tend to become clogged with debris flow lobes, the result of frequent hyperconcentrated flows, and debris flows during times when the stream has a sustained discharge. These debris lobes are usually very coarse grained, locally armored the channel, and thus greatly increase the response time of the channel to adjust to a tectonically-induced change in gradient. Due to these differences in sediment transport processes, we proceed on the premise that ephemeral channels will respond to a perturbation such as a rising anticline in more complex ways other than making subtle changes in sinuosity (Ouchi, 1985; Harbor, 1998) or number of braid bars (Germanoski and Schumm, 1993), as has been documented for perennial channels.

Perennial channel morphology adjusts primarily in response to changes in discharge and secondarily to changes in slope. Slope refers to both channel slope and valley slope, in which the sinuosity of the channel is the compensation between the two. Ouchi (1985), Germanoski and Schumm (1993), and Harbor (1998) developed models of perennial alluvial river response to active tectonics using flume experiments and empirical field data (summarized in Holbrook and Schumm, 1999). Both alluvial braided and meandering channels change channel pattern and experience aggradation and degradation in response to changes in valley slope. A braided alluvial perennial channel that encounters an area of uplift will respond by creating alternate bars with a braiding tendency upstream of the uplift, terraces, and an area of degradation in the axis of the uplift, and a strongly bar-branched pattern downstream of the uplift.

**METHODS**

Six transverse ephemeral channels were chosen to cover the along-strike exposure of the Cougar Buttes anticline (Figs. 2, 3, and 4). This anticline was chosen because of its clear topographic expression of folding and the solid evidence of an active thrust fault in its core. The relative age of the deformed alluvial fan strata indicates continued folding through the late Pleistocene. From east to west the investigated channels are Blackhawk wash, Doubleknob wash, East Middle wash, Middle wash, Slick wash, and Control wash (Fig. 4). Each channel was divided into 5–6 reaches, A through F, each ~0.5 km in length, where A is the distal upstream reach, B is the proximal upstream reach, C is the reach through the fold axis, D is the proximal downstream reach, E is the distal downstream reach, and F is the downstream fan gradient.

A high-resolution survey (points spaced typically less than 10 m) of each channel and interfluve adjacent to the channel was made using a Sokkia laser theodolite. From these surveys, longitudinal profiles were plotted to illustrate the gradient of each channel normal to the growing structure (Fig. 4). A representative cross section of the entire valley width was also surveyed for each reach (Fig. 5). From these cross sections, the width (w) and depth (d) of the channel was measured, allowing the width-to-depth ratio (w:d) to be calculated (Tables 1 and 2). Channel width in the field was defined by the break in slope between the channel bank and fan surface, or the channel bank and terrace surface. Channel sinuosity (P), the length of the surveyed channel (l), divided by the length of the valley (L), was calculated for the entire length of each stream, and for individual reaches. Using a method modified from Wolman (1954), the grain size
of coarse (> 2 cm) alluvium from the bed of Middle and Blackhawk washes at the location of the measured cross sections, as well as alluvium from a debris flow lobe in Slick, Middle, Doubleknob, and Blackhawk washes were sampled. We placed a measuring tape longitudinally in the channel, and the grain closest to every 0.5 m interval with a diameter greater than 2 cm was measured along its intermediate (b) axis. The number reported is simply the average of at least 100 grains.

The number and length of individual braid bars was recorded for channels that traverse the Cougar Buttes anticline and for a channel that encounters a northwest-trending uplift (Woodlane wash, Fig. 4) following the methods outlined by Germanoski and Schumm (1993). In each reach, data were collected in a representative reach 100 m in length. These data allow the modified braiding index (B.I.) (Germanoski and Schumm, 1993) to be calculated,

$$B.I. = 2 \left( \frac{\sum L_b}{L_r} \right) + \frac{B_n}{L_r}$$

where $L_b$ is the length of a single measured bar, $L_r$ is the length of the reach, and $B_n$ is the total number of bars measured in the reach.

**Figure 3.** Geologic map and photograph of the Cougar Buttes anticline. Photo (view looking west) shows the fold cut by Middle wash. The fault plane (solid white line), Tertiary Old Woman Springs (Tow), Tertiary Cushenbury Springs (Tcsu), Quaternary colluvium (Qc), Quaternary very old fan (Qvof 2), Quaternary young fan (Qyf 3), and the base of a middle (?) Pleistocene petrocalcic horizon (dashed black line) are shown. The petrocalcic horizon holds up the limbs of the fold and serves as a marker bed for offset on the fault. The photo illustrates the geometry of the fold, with a steep backlimb, gentle forelimb, and north-verging thrust fault. Fan units on the geologic map are modified from Powell et al. (2000). Location of detailed topographic survey maps A, B, and C of Figure 12 (insets) are shown. Map illustrates the fold axis and fault plane of the anticline and locations of transverse drainages utilized by Quaternary fans to traverse the fold.
Figure 4. Topographic map of the Cougar Buttes anticline showing the locations of six transverse channels and reaches A through E for each channel. See Figure 2 for location. Channel longitudinal profiles (lower line) and interfluve profiles (upper line) for each stream are shown. Longitudinal profile scale is in meters, and elevation is above an arbitrary datum. Note different scales between wash profiles; vertical exaggeration varies between 16x and 25x. Profiles illustrate the varying topographic expression of the anticline along strike. Note the generally concave-up stream profiles, without significant knickpoints. In reach B of Middle and Doubleknob washes, the channel profile is on or above the interfluve profile, illustrating significant sediment deposition behind the fold. Two northwest-trending uplifts (dashed lines) north of the Cougar Buttes anticline are highlighted, one traversed by Doubleknob wash, and the other traversed by Woodlane wash (detailed inset of Fig. 8). The location of detailed topographic maps A, B, and C of Figure 12 (inset) are shown.
RESULTS

Channel Morphology and Pattern Across a Growing Fold

Notable changes in channel pattern and less dramatic changes in channel morphology and grain size occur between adjacent reaches where the ephemeral channels traverse the Cougar Buttes anticline (Table 1). The alluvium that is being carried by channels on the limestone provenance piedmont is poorly sorted and subangular, but generally fines downstream. Gravel, sand, and silt are only minor constituents of this alluvium, which is dominated by the cobble and greater size fraction, with the average grain size of clasts larger than cobbles ranging from ~20–66 mm (Table 1). Grain size is noticeably larger for those parts of the channel that contain debris flow bars and levees. There is no obvious selective size sorting of channel or alluvial fan deposits within or on the flanks of the anticline.

The most distinct channel morphology adjustments are in the channel width-to-depth (w:d) ratio (Figs. 5, 6, and 7A). A large increase in w:d values from reach A to B, a decrease in reach C, and an increase in reach D is a general trend consistent for each stream and best expressed in Middle wash (Fig. 6). The overall channel pattern, as seen in the photos of reaches A, B, and C (Fig. 6) is consistent with the w:d variations. Reach A of streams that traverse the Cougar Buttes anticline is generally a small single channel ~1 m wide, typically incised 1–2 m into the fan surface. Reach B is distinctly braided, with multiple active...
channels, each ~1 m wide, with a substantially wider valley bottom. This reach usually contains active bars and debris flow lobes, and is the storage site for a large wedge of sediment backed up against the fold limb “dam.” This sediment wedge is evident in the longitudinal profiles of Middle and Doubleknob washes, where the channel is on or above the fan surface in reach B (Fig. 4). As the stream enters the fold (reach C), the multiple active channels coalesce into a single thread channel ~3–6 m wide. Reaches C and D store relatively large amounts of alluvium like reach B; however, they do so on the channel flanks as terraces or vegetated bars. In the hinge of the fold, the terrace treads can be up to 1 m higher than the active channel bottom, but further downstream in the lowest stretch of reach C and the entirety of reach D, the terraces and bars tend to only be 20 or 30 cm above the channel bottom. The vegetation on these terraces usually consists of small- to medium-sized shrubs and creosote bushes that likely act to stabilize these landforms. Reach D is similar to reach C; however, the channel is usually only incised into the fan surface 2–5 m, rather than 10–20 m as in reach C. Reach E is a single channel ~2–4 m wide, incised 0.5–1 m into the fan surface, and lacks vegetated bars.

Changes in channel pattern and morphology are also evident from the modified braid index (B.I.) calculated for representative reaches of the channels that traverse the Cougar Buttes anticline (Fig. 7B). In a flume study, Germanoski and Schumm (1993) calculated the braid index for both sand and gravel bed perennial alluvial channels. The B.I. was calculated for channels in equilibrium, for channels experiencing aggradation, and for channels experiencing degradation due to simulated tectonic perturbation. For all flume runs, B.I. consistently increased for aggrading channels, and decreased for degrading channels. Across the Cougar Buttes anticline, the measured B.I. consistently increases from reach A to reach B, as the ephemeral channels begin to aggrade approaching the backlimb of the anticline (Fig. 7B, dashed and dotted lines). B.I. decreases from reach B to reach C through the core of the anticline, as the channels incise and preserve a terrace in the axis of the fold. Lastly, B.I. increases from reach C to reach D as the channels return to the grade of the fan. In contrast, astride the western plunging tip of the fold, the terrace treads can be up to 1 m higher than the active channel bottom, but further downstream in the lowest stretch of reach C and the entirety of reach D, the terraces and bars tend to only be 20 or 30 cm above the channel bottom. The vegetation on these terraces usually consists of small- to medium-sized shrubs and creosote bushes that likely act to stabilize these landforms. Reach D is similar to reach C; however, the channel is usually only incised into the fan surface 2–5 m, rather than 10–20 m as in reach C. Reach E is a single channel ~2–4 m wide, incised 0.5–1 m into the fan surface, and lacks vegetated bars.

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**Figure 6.** Chart of the width-to-depth ratio of a representative portion of each channel reach for Middle wash as it crosses the Cougar Buttes anticline. The axis of the fold is centered on reach C. Photos illustrate the disparity in gross channel pattern morphology between each reach. Vertical arrows illustrate channel boundaries used for width-to-depth (w:d) ratio calculations. (A) Typical channel morphology of reach A; channel is narrow and only slightly incised into the fan surface. Fieldbook is highlighted for scale (~0.2 m in length). (B) Debris flow lobes and braided pattern of reach B, upstream of the fold. Distance between vertical arrows is 8 m. (C) Typical channel morphology of reach C in the fold axis; notice the vegetated terrace to the left of the channel, standing ~1 m above the channel bed elevation. Distance between vertical arrows is 5 m. View looking downstream.

**Channel Morphology and Pattern Across Small Faults**

Longitudinal changes in ephemeral channel pattern and morphology are not restricted to those streams that cross the topographically obvious strike length of the Cougar Buttes anticline. For example, northwest-trending faults synthetic to the Helendale fault strike parallel to the fold, a shallow gradient as it flows parallel to the fold, a shallow gradient as it traverses the fold axis, and then a steeper gradient on the downstream side of the fold (Fig. 8B).

In addition to changes in gradient, these channels also adjust their patterns (Figs. 7B, 8C, and 8D). Both show a higher braiding index in reach B with respect to reach C, with a wider range in the index for Woodlane wash, which flows transverse across the structure rather than being deflected by it. Figure 8C shows a representative reach of the deflected drainage, Blackhawk wash, which is ~6 m wide, flat-bottomed, lacks any vegetated bars, and is incised only tens of
Figure 7. (A) Channel w:d ratios plotted with respect to alluvial fan provenance and channel reach. The axis of the growing structure is centered on reach C and is highlighted by the shaded area. The streams located on the granite provenance piedmont fans are indicated by the dashed lines. A key feature to note is that the channels generally become more narrow and deep (lower w:d) in the C reach (solid lines). (B) Plot showing the braid index (B.I.) calculated for channels that traverse growing structures. Higher B.I. values indicate a large number of smaller braid bars that develop as a channel is aggrading, whereas lower B.I. values indicate a small number of larger braid bars that remain as a channel is degrading. The axis of the growing structure is centered on reach C and highlighted by the shaded area. The data are organized into three categories. The solid lines refer to two streams (Control and Slick washes) that traverse the plunging western tip of the Cougar Buttes anticline. Note that these streams increase B.I. through reach C. The dashed lines refer to three streams (Doubleknob, Lower Doubleknob [reaches D, E, and F], and Middle washes) that traverse the high-standing part of the core of the Cougar Buttes anticline, and have high B.I. values in reach B. The dotted lines refer to the two streams that cross small upwarps (Woodlane and Blackhawk washes) north of the Cougar Buttes anticline.

EPHMERAL STREAM RESPONSE TO GROWING FOLDS

Topographic ridges similar to the Cougar Buttes anticline are not present along the piedmont west of the Helendale fault. Nevertheless, actively growing folds are suspected, based on the mapped distribution of folded Cushenbury Springs Formation and mid–late Pleistocene alluvial fans. The alluvium in channels in the granite provenance piedmont contrasts strongly with alluvium of the limestone provenance piedmont. Granitic provenance sediment is dominated by the coarse sand to granule size fraction, and is relatively sparse in the cobble and larger grain sizes, although coarse, subangular to subrounded granitic pebbles to boulders do exist. This alluvium is also representative of adjacent alluvial fan deposits. The soils that form in these deposits do not constitute durable horizons capable of holding up limbs of a rising anticline (Eppes et al., 2002).

Pitzer Buttes wash and Big Burn wash (Fig. 9) both head on granitic alluvial fan surfaces west of the Helendale fault and flow transverse to structures suspected to be of similar scale to the Cougar Buttes anticline. The drainage basin areas of Pitzer Buttes wash and Big Burn wash are comparable to the drainages studied in the limestone fan region east of the Helendale fault. Big Burn wash traverses a high-angle reverse fault that forms a scarp with up to 20 m of relief locally. The footwall of this fault is folded into a broad anticline with little to no topographic expression. Further down fan, Pitzer Buttes wash crosses an anticline that is expressed in the map pattern and as a broad convexity in the fan surface (Figs. 10 and 11). Both streams are transport-limited systems and are dominated by an abundance of granitic grus supplied from the fan surface. Big Burn wash is proximal to the mountain front. Consequently it exhibits a steeper gradient and contains many in-channel, large (0.5 m or larger) centimeters into the fan surface. In comparison, Figure 8D shows that Woodlane wash changes from a wide, flat-bottomed channel 0.3 km upstream of the fold, similar to Blackhawk wash, to a braided channel with active and vegetated bars immediately upstream and into the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream of the structure, Woodlane wash returns to the channel morphology it displays upstream of the structure.

Doubleknob wash encounters a similar north-west-trending upwarp downstream of the Cougar Buttes anticline (Fig. 4, dashed line). Reaches D, E, and F of Doubleknob wash illustrate a response similar to other ephemeral streams that encounter such an uplift; immediately upstream of the structure reach D aggrades and is choked with sediment (Figs. 4 and 5). In the axis of this structure (reach E), the channel incises into the fan surface and preserves a vegetated terrace. Finally, after the stream passes any influence of uplift, reach F returns to a wide single channel only incised 0.5 m into the fan surface. To summarize, the response of both Woodlane wash and Doubleknob wash to a small upwarp is a change in channel pattern to a distinct braided morphology, with an increase in the number of braid bars (increased B.I.), temporarily storing sediment in the reach immediately upstream of the fold, before the washes incise into the fold axis and return to the grade of the fan.

Channel Morphology and Pattern Across Suspected Growing Folds

Figure 8D shows that Woodlane wash changes from a wide, flat-bottomed channel 0.3 km upstream of the fold, similar to Blackhawk wash, to a braided channel with active and vegetated bars immediately upstream and into the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream of the fold, similar to Blackhawk washes) north of the Cougar Buttes anticline. Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). Downstream the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline).
granite boulders supplied from the fan surface that are likely not fluvially transported.

The longitudinal profiles and representative cross sections for reaches A through F of Pitzer Buttes wash and Big Burn wash illustrate how these channels are responding to suspected deformation along a reverse fault and two separate growing anticlines (Fig. 11). Big Burn wash encounters the fault scarp and changes from a narrow (~1 m wide) channel that is only slightly incised into the uplifted hanging wall fan surface upstream of the scarp (Fig. 11A, reach A), to a boulder-dominated reach astride the scarp (Fig. 11A, reach C), and finally to a highly braided reach in the down-dropped footwall (Fig. 11A, reach D). As the channel encounters the footwall anticline, it incises (Fig. 11A, reach E), leaving a large high terrace (~3 m above the current channel bed) in the axis of the fold. In the anticline’s forelimb, the channel is less incised, and its gradient is indistinguishable from the gradient of the fan (Fig. 11A, reach F).

As Pitzer Buttes wash crosses the Pitzer Buttes anticline (Figs. 9, 10, and 11), channel pattern variability between reaches is of similar style, but of less magnitude than that which occurs along washes that traverse the Cougar Buttes anticline. Pitzer Buttes wash is a narrow (1.5 m wide) channel not incised into the fan surface upstream of the uplift (Fig. 11B, reach A). Proximal to the uplift, the channel widens to ~3 m and slightly grades (Fig. 11B, reach B). In the axis of the uplift, the channel is ~4 m wide and contains low vegetated bars (Fig. 11B, reaches C and D). Downstream of the uplift, the channel returns to the grade of the fan, is ~2.5 m wide, and lacks bars (Fig. 11B, reach E).

Transverse Drainages

The ephemeral streams that traverse growing folds, small upwarps, and suspected growing
folds exhibit a range of general drainage patterns that are possibly related to their genesis. We observe at least three drainage patterns adopted by streams that encounter a growing fold (Fig. 12). The first drainage pattern is characterized by small, steep gullies that occur on the forelimb and crest of the fold, but do not completely breach the crest to the backlimb to form a complete transverse channel (Fig. 12A). These gullies are fed by runoff generated on the steepened forelimb of the fold, aided by the shallow, impermeable petrocalcic horizon. The second drainage pattern is characterized by channels that occupy narrow, shallow canyons that lack fluvial terraces, and that are hydrologically connected to alluvial fan deposits banked up against the backlimb of the fold (Fig. 12B). Tributaries to these channels flow in narrow, deep, strike valleys pinned between the backlimb and the banked alluvial fan surface upstream of the fold. The third drainage pattern is characterized by nearly linear channels that cut growing folds in deeply incised canyons tens of meters wide (Fig. 12C). Holocene alluvial fans upstream of the fold are funneled through these canyons and effectively transport water and sediment from the mountain front through the topographic barrier represented by the fold (Fig. 4). Tributaries to these transverse channels occupy strike valleys in the breached core of the anticline. Large transverse streams that head in the mountain front have an average spacing of 1.93 km, consistent with the average spacing of major drainages in the San Bernardino Mountains (Table 3). In contrast, smaller streams that head on the alluvial fans have an average spacing of 0.28 km.

DISCUSSION

Ephemeral Channel Response to Growing Folds

The responses of ephemeral alluvial stream channels on the San Bernardino piedmont to growing folds and active faults share some similarities to those documented for perennial braided alluvial channels (Harbor, 1998; Holbrook and Schumm, 1999; Schumm et al., 2000), but there are some notable differences. The most consistent response of all streams studied, especially those that traverse the Cougar Buttes anticline, is braiding and storing sediment upstream of the fold in reach B (sometimes reaching up to 500 m upstream of the fold axis), incision and terrace preservation in reach C, and a slow decrease in the number of bars in reach D (Figs. 7B and 13).

Aggradation and degradation dominate the ephemeral channel responses to growing folds. An index of aggradation, such as the braiding index, mimics the observed results in the analogue models of Germanoski and Schumm (1993). In contrast, perennial alluvial channels accommodate the gradient changes imposed by a growing fold primarily through sinuosity and w:d changes and to a lesser degree aggradation and degradation. We suggest that the lack of systematic sinuosity changes, and variable response of w:d ratios in ephemeral channels can be traced back to the relatively unstable channel banks, frequent debris flow processes, and slower response times that characterize these channels. Collectively, these characteristics, less the debris flows, describe precisely those of a perennial braided or meandering alluvial channel that is being overwhelmed by an active uplift (Harbor, 1998). In this situation, perennial channels abandon changes in channel pattern and cross-sectional form in favor of aggradation and degradation. Short spatial variations in erosion and deposition in perennial channels introduce strong nonlinearities in sediment transport and favor reaches with unstable banks, variable channel widening, and temporary storage of sediment in braid bars.
Figure 10. Geologic map of the Pitzer Buttes anticline and Pitzer Buttes wash. The Tertiary Cushenbury Springs Formation is informally broken into upper, middle, and lower units, defining the fold. See Figure 2 for location. Note the lack of any topographic expression of the fold.
Ephemeral channels we studied do encounter a by incision (Holbrook and Schumm, 1999). The stream increases in sediment supply induced erosion imposed by gradient changes or to down-uplift is typically attributed to physical barriers, but rather to these two channels that head on the alluvial fan, or perhaps these channels encounter slower rates of fold growth as they cross the plunging axial line of the anticline.

Tectonically driven changes in transport gradient or watershed-driven changes in hydrology and sediment yield are the two competing factors in controlling the variations in braiding behavior. Gradient changes include reach-scale tilting as well as local topographic barriers produced by the steep fold limbs. The longitudinal profiles (Fig. 4) show that the channels that traverse the Cougar Buttes anticline do not have knickpoints coincident with the fold limbs. From this we infer that these channels are able to incise at the rate that the fold is rising. In contrast, the long profiles of channels traversing the suspected growing folds in the granitic provenance piedmont are broadly convex. Again we appeal to relative sediment flux and texture to explain the channel behavior on the granitic provenance piedmont. The channels here are primarily transporting nearly cohesionless grus. The abundance of this sediment type leads to unstable, low-relief channel banks with more consistent w:d ratios, as compared to channels on the limestone piedmont (Fig. 7A; Tables 1 and 2). Braid bars within these channels are difficult, if not impossible, to define or distinguish from the surface texture of the granitic provenance fans. Where we were able to collect channel morphology data in the granitic provenance fans, we find that the w:d ratio in reach C is slightly higher than in reach B, a result shared with Slick wash as it crosses the Cougar Buttes anticline (Fig. 7A). In the case of Slick wash, the slightly wider channel occurs near the plunging tip of the fold where uplift rates are presumed to be relatively low. Similar, qualitative changes in the braiding index are indicated from mass wasting, and their loss of discharge downstream to both infiltration and evaporation.

There is a surprising range of ephemeral channel responses between the growing folds, active faults, and suspected growing folds. Qualitatively, the amount of sediment in the channels of reach B is related to the size of the drainage basin and the parent material/sediment provenance. Streams that head in the mountain front have a greater magnitude of change in channel pattern morphology when they encounter the fold and often have coarser debris flow lobes in reach B compared to streams that head on the alluvial fans. For example, both Control and Slick washes have braided channel patterns in reaches B and C; however, the braid index is highest in reach C of these channels, rather than reach B as it is for the majority of other transverse channels (Fig. 7B). This probably stems from the smaller amounts of sediment supplied to these two channels that head on the alluvial fan, or perhaps these channels encounter slower rates of fold growth as they cross the plunging axial line of the anticline.

(Harbor, 1998). We attribute these responses on the San Bernardino piedmont not necessarily to an overwhelming tectonic forcing, but rather to the inherent nature of sediment transport and hydrology of ephemeral channels. Thus we suggest that the responses that we documented would be representative for a wide range of rates of tectonic deformation.

Braiding in channels being affected by active uplift is typically attributed to physical barriers imposed by gradient changes or to downstream increases in sediment supply induced by incision (Holbrook and Schumm, 1999). The ephemeral channels we studied do encounter a physical barrier in the form of the backlimb of the rising fold, and braiding is well expressed in reach B. However, ephemeral channels are not as efficient at sourcing and transporting sediment from the uplift axis because of the infrequent channel modifying discharges. The result is small alternate bars in reach D and a widened channel that returns to the grade of the fan in reach E. A decrease in bar size where the channel is relatively incised is at odds with the general response of perennial channels, which tend to develop larger bars in incised reaches. The difference between ephemeral and perennial channels in this case probably reflects primarily the importance of debris flow processes and secondarily the still poorly confined nature of incised ephemeral channels, their weak channel banks, their localized contribution of sediment

Figure 11. Longitudinal profile, interfl uve profile, and channel cross sections for Big Burn wash and Pitzer Buttes wash. Note the different scales for the profiles and cross sections. Profiles are plotted in meters above an arbitrary datum. 10x vertical exaggeration for Big Burn wash profiles and 20x vertical exaggeration for Pitzer Buttes wash longitudinal profiles. No vertical exaggeration of channel cross sections. Note the broad convexity in both stream profiles and in the interfl uve profiles in the areas of the broad anticlinal structures. Changes in channel pattern are similar to, but of a lesser magnitude than those observed in channels that traverse the Cougar Buttes anticline.
for the granitic provenance channels from photographs and the longitudinal profile of the channel and fan surface (Fig. 11). We speculate that like perennial channels, widening and braided bar production of ephemeral channels occur initially in response to changes in valley gradient imposed by a growing structure, especially where sediment flux is not overwhelmed by up-basin sources, the sediment texture is coarse, and the sediment has cohesion (Figs. 13A and B). However, where the sediment flux from up-basin sources is large, the sediment texture is fine, and the sediment has low cohesion, these characteristics drive an ephemeral channel to respond differently than the typical perennial channel (Fig. 13C).

Applications of Ephemeral Stream Response to Active Tectonics

Shortening associated with the uplift of the San Bernardino Mountains is accommodated in the complicated zone of faults and folds between the Big Bear and Mojave blocks (Fig. 1). East-west-oriented growing anticlines, like the Cougar Buttes anticline, are restricted proximal to the San Bernardino mountain front. Further into the foreland, folds and faults trend to the northwest, presumably following the prevailing structural grain of the Mojave block. Many of the thrust faults in this setting are blind. Only larger thrusts, such as the one that cores the Cougar Buttes anticline, are emergent. The morphology of ephemeral channels we have studied suggests that deformation is not restricted to the structure furthest from the mountain front, but rather stretches across the entire foreland, albeit at different rates. It also suggests that both portions of the piedmont astride the Helendale fault (Fig. 2) are actively deforming.

Ephemeral channel morphology could be used as a tool to estimate the potential rupture length of earthquakes occurring on blind or recently emergent thrust faults such as the Cougar Buttes anticline. Because rupture length and moment magnitude are highly correlated (Wells and Coppersmith, 1994), identifying the tectonic fingerprint in ephemeral channels could serve as an aid to correctly map the minimum lengths of active faults and better delineate the seismic hazards. The ephemeral channel response along with the regional geomorphology indicate both a wider zone of shortening as well as longer strike length of the thrust faults than is observed in the general topography alone, especially at the resolution of 6 m map contours. For example, clear topographic expression of the Cougar Buttes anticline on a topographic map extends for 2 km, ending just west of Slick wash (topographic contours of Fig. 4). However, the behavior of Control wash (Figs. 5 and 7B) and the convexity in the interfluve longitudinal profile suggest that the anticline extends at least 1 km further west (Fig. 4). A thrust fault 2 km long beneath the Cougar Buttes anticline could generate an earthquake with a moment magnitude of 5.4, whereas a 3 km fault would be capable of generating an earthquake with a moment magnitude of 5.7.

Thrust faults west of the Helendale fault would be literally blind where they do not reach the surface or figuratively blind in the sense that

Figure 12. (A) Topographic map showing the initial stage of headward erosion of a small gully on the forelimb of the Cougar Buttes anticline just west of Slick wash. The drainage on the upstream side of the fold is forced to flow parallel to strike until finding a water gap. (B) Topographic map showing an area just west of Doubleknob wash, where a gully has recently breached the anticline axis. The valley is narrow, does not have any terraces, and allows channels that flow parallel to strike to traverse the fold axis. (C) Topographic map of Doubleknob wash, a location of a fully integrated water gap. The valley is wider than location B, and contains a terrace ~1 m above the current bed elevation. Scale is in meters. Contours in meters with respect to the surveying base station. See Figure 4 for locations.
they do not build anticlinal ridges because of the soil development and erosion characteristics of deforming granitic fan materials (Eppes et al., 2002). Longitudinal profile surveys of two channels on the granitic piedmont fans reveal channel morphology adjustments similar to those observed on the limestone piedmont fans as if an actively rising structure were present. In this case, we suggest that the ephemeral streams are antecedent channels across an actively rising fold. The ephemeral channels suggest that blind thrust faults permeate the San Bernardino piedmont, even in locations where there is little topographic expression of their presence. The Helendale fault in this view is not a major boundary to north-directed shortening on the San Bernardino piedmont.

**Transverse Drainages and the Kinematics of Growing Folds**

Antecedence is a common explanation for transverse drainages across rising folds (Ollier, 1991). Coincidence in the spacing of large channels (Middle, Doubleknob, and Blackhawk washes) across the Cougar Buttes anticline with the mountain front drainage spacing (Table 3) and the fact that these large transverse channels are not convex or characterized by knickpoints (Fig. 4) is consistent with an antecedent origin. Apparently, these large ephemeral channels are able to incise at rates equal to or in excess of the rate of fold growth. The smaller channels that cross the anticline, like Slick wash, are slightly convex (Fig. 4) and may owe their origin to initial consequent drainages, stream piracy (Keller et al., 1999), or thrust fault dip (van der Beek et al., 2002). We propose a three-stage model for the development of transverse drainages across rising anticlines (Fig. 12).

Emergence of the Cougar Buttes anticline initially deflects up-fan drainage around the uplift, but the largest channels are able to maintain their general courses and proceed on an evolutionary pathway toward becoming antecedent drainages. At the same time, increased slope on the emerging forelimb of the fold fosters small gullies to form (Fig. 12A), which are aided by the petro-

**TABLE 3. AVERAGE SPACING OF TRANSVERSE DRAINAGES AT THE COUGAR BUTTES ANTICLINE**

<table>
<thead>
<tr>
<th>Method</th>
<th>Mountain drainages (km)</th>
<th>Fan drainages (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse USGS blue line channels</td>
<td>1.93</td>
<td>0.76</td>
</tr>
<tr>
<td>Transverse field-determined channels</td>
<td>1.93</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Emergence of the Cougar Buttes anticline initially deflects up-fan drainage around the uplift, but the largest channels are able to maintain their general courses and proceed on an evolutionary pathway toward becoming antecedent drainages. At the same time, increased slope on the emerging forelimb of the fold fosters small gullies to form (Fig. 12A), which are aided by the petro-

**Figure 13.** (A) Schematic block diagram illustrating the general model for changes in ephemeral stream channel pattern and morphology responding to a growing fold such as the Cougar Buttes anticline. Channel pattern changes from a narrow, slightly incised channel in reach A, to a wide, highly braided pattern in reach B. The channel incises, preserving a terrace in reach C, becoming less incised, and containing small vegetated bars in reach D, before finally returning to the grade of the fan in reach E. (B) Variation of the general model for ephemeral stream channel response for slowly growing folds, such as the plunging western tip of the Cougar Buttes anticline. This response varies from diagram A because while the channel is still braided in reach B, it becomes more intensely braided in reach C, before mimicking the response in reaches D and E. (C) Variation of the general model for ephemeral stream channel response for channels with high alluvial fluxes, and/or alluvium of low cohesion, such as at the Pitzer Buttes anticline. Channel pattern changes from a narrow, unincised channel in reach A, to a wider, aggraded channel in reach B. The channel widens again in reach C, storing sediment as low, vegetated bars, before narrowing and returning to the grade of the fan through reach D and into reach E.
calcic layer retarding infiltration and funneling drainage into these small channels. These gullies are able to erode headward, toward the crest of the fold. If this headward erosion is coincident with significant fan aggradation on the upstream flank of the anticline, the fold axis can be breached as fan discharge is funneled into a gully head (Fig. 12B). Once the backlimb is fully breached, the up-fan drainage is no longer forced around the fold, but instead can take advantage of the newly integrated water gap. The increased drainage area and discharge allows the channel to rapidly enlarge the water gap (Fig. 12C). In this model, different sizes of transverse water gaps merely represent channels at different stages of transverse development. The drainage spacing of the smaller, presumably pirated transverse channels might be taken as either the minimum drainage area necessary to maintain a transverse drainage across the rising fold, or the minimum drainage area necessary to generate a consequent stream that will ultimately breach an inactive fold as it is exhumed (Table 3). In other words, an along strike distance of ~0.28 km could be the threshold needed before a headward-eroding gully is able to collect enough discharge, even if infrequently, to be able to breach the anticline. Although these examples highlight locations of more evolved drainage on the eastern portion of the Cougar Buttes anticline and less evolved drainage on the western portion, we do not intend to imply westward growth of the structure. Examples of the three stages of transverse drainage evolution are observed along the entire length of the anticline.

The headward-eroding gullies on the forelimb of the Cougar Buttes anticline may be a feature restricted to those folds whose forelimbs are significantly more gentle than the backlimbs. Because the gradients of most forelimbs are typically steeper than the backlimb, there are few headward-eroding gullies that can tap alluvial fan deposits aggrading against the backlimb. But for the Cougar Buttes anticline, the long, impermeable forelimb surface fosters large gully development and the eventual integration across the fold axis where aggradation against the steep, dam-like backlimb outpaces fold growth. Here the development of transverse drainages is controlled primarily by limb dip, which in this particular case does not seem to be closely controlled by the dip or the vergence of the thrust fault, or at least that portion of the fault that is exposed at the surface. For this particular location, the results are not consistent with the van der Beek et al. (2002) conclusion that the primary control on transverse drainages is the dip of the thrust fault plane, insofar that thrust plane dip is highly correlated with the dip and length of the fore and back limbs.

CONCLUSIONS

Ephemeral streams on the San Bernardino Mountain piedmont display a diverse range of channel morphologic and pattern changes in response to actively growing folds. Everything else being equal, ephemeral stream responses deviate from better documented perennial stream responses by being aggradation-incision and sediment texture-cohesion driven rather than gradient-sinusosity driven. The specific findings of this study are:

1. Ephemeral alluvial channels respond to changes in transport gradient associated with both the backlimb and forelimb of emergent anticlines cored by a (commonly blind) thrust fault. The response is expressed as changes in channel w:d ratio and in the braiding pattern as the stream crosses the uplifted area. Upstream of the fold, the ephemeral channel becomes distinctly braided with an increase in the number of the braid bars and braid index (B.I.), and an increase in the width-to-depth (w:d) ratio. In the axis of the fold, the channel incises, preserving a terrace and effectively increasing the size of braid bars at the expense of the number of bars. Both B.I. and w:d decrease in the axis of the fault. Downstream of the fold, the w:d ratio and the B.I. increase, marked by an increase in the number of braid bars and a decrease in their size before the channel grades into the distal fan.

2. Ephemeral streams behave most like braided perennial streams that are incising or aggrading in response to rapid rock uplift or subsidence. Aggradation and incision introduce point sources or sinks of sediment resulting in nonlinear transport of alluvium through the channels (Harr bar, 1998). Ephemeral channels may always tend toward these responses irrespective of the uplift or subsidence rate because of the infrequent channel modifying flows.

3. Like perennial channels, widening and braided bar production in ephemeral channels occurs initially in response to changes in valley gradient imposed by a growing structure, especially where sediment flux is not overwhelmed by up-basin sources, the sediment texture is coarse, and the sediment has cohesion (Fig. 13A). However, where the sediment flux from up-basin sources is large, the sediment texture is fine, and the sediment has low cohesion, these characteristics drive an ephemeral channel to respond differently than the typical perennial channel. Whereas perennial channels are strongly braided downstream of an uplift, ephemeral channels return to the grade of the fan because of less efficient sourcing and transport of sediment during typical episodic and flashy discharge events. Overall, braiding patterns are more persistent, changes in channel pattern dominate the response to tectonic perturbation, and a greater variability of response exists in ephemeral channels compared to perennial channels.

4. Ephemeral stream channel morphology suggests that shortening associated with the uplift of the San Bernardino Mountains is being accommodated as a series of faults and folds in a broad complex zone between the Big Bear and Mojave blocks. Shortening is accommodated on growing folds with emergent thrust faults, along strike projections of these folds with blind thrust faults, and on small upwarps that may represent the early stages of growing anticlines. Based on channel morphologic patterns, not topology, the strike lengths of thrust faults may be greater by perhaps as much as 50% than what is mapped on the San Bernardino piedmont, significantly increasing the seismic hazard that could result from the rupture of one or more segments.

5. It is possible for consequent streams that are born as gullies on the gentle forelimb of an anticline to evolve headward, capturing fan deposits aggraded against the steep backlimb. Such capture leads to the development of a transverse drainage. A drainage area of ~0.3 km² upstream of the Cougar Buttes anticline appears to be the smallest threshold size for maintaining the channel across the rising fold.

ACKNOWLEDGMENTS

This manuscript has greatly benefited from reviews by David Harbor, Dallas Rhodes, and Ellen Wohl. We thank Lehigh University and the Palmer Grant for helping to fund this study. This research was completed while S. Pearce was at the Department of Earth and Environmental Sciences, Lehigh University, and M. Eppes was at the Department of Earth and Planetary Sciences, University of New Mexico. S. Pearce thanks Justin Pearce for his encouragement and support, and Byron Kurkowski and Carrie Dolton for their help in the field.

REFERENCES CITED


Burbank, D.W., and Verges, J., 1994, Reconstruction of