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Influence of late Holocene hillslope processes and landforms on modern channel dynamics in upland watersheds of central Nevada

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Abstract

Stratigraphic, geomorphic, and paleoecological data were collected from upland watersheds in the Great Basin of central Nevada to assess the relationships between late Holocene climate change, hillslope processes and landforms, and modern channel dynamics. These data indicate that a shift to drier, warmer climatic conditions from approximately 2500 to 1300 YPB led to a complex set of geomorphic responses. The initial response was massive hillslope erosion and the simultaneous aggradation of both side-valley alluvial fans and the axial valley system. The final response was fan stabilization and axial channel incision as fine-grained sediments were winnowed from the hillslope sediment reservoirs, and sediment yield and runoff processes were altered. The primary geomorphic response to disturbance for approximately the past 1900 years has been channel entrenchment, suggesting that the evolutionary history of hillslopes has produced watersheds that are prone to incision. The magnitude of the most recent phase of channel entrenchment varies along the valley floor as a function of geomorphic position relative to side-valley alluvial fans. Radial fan profiles suggest that during fan building, fan deposits temporarily blocked the flow of sediment down the main stem of the valley, commonly creating a stepped longitudinal valley profile. Stream reaches located immediately upvalley of these fans are characterized by low gradients and alternating episodes of erosion and deposition. In contrast, reaches coincident with or immediately downstream of the fans exhibit higher gradients and limited valley floor deposition. Thus, modern channel dynamics and associated riparian ecosystems are strongly influenced by landforms created by depositional events that occurred approximately 2000 years ago. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The restoration and management of stream and riparian ecosystems has become a national and international topic of concern (National Research Council, 1992; Naiman et al., 1993; Tellman et al., 1993; Kentula, 1997), and the number of restoration programs in the US has increased dramatically within the past decade. The success of these programs depends on our ability to understand and predict changes in channel form and process in response to

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natural disturbances (e.g., climate change and tectonism) and anthropogenic disturbances (e.g., grazing, mining, logging, and road construction) over a continuum of temporal and spatial scales. The development of quantitative models describing the response(s) of fluvial systems to disturbance has proven problematic. Different rivers, or in some cases different reaches of the same river, have been shown to exhibit divergent responses to a single disrupting event (Schumm, 1973; Schumm and Brakenridge, 1987). Moreover, there is a growing realization that an individual basin possessing a given set of morphometric and biological properties can experience different geomorphic responses to disturbances of similar magnitude (Newson, 1980; Beven, 1981; Kochel et al., 1987; Kochel, 1988).

Multiple factors contribute to the difficulties in predicting channel responses to disturbance (Schumm and Brakenridge, 1987), including a poor understanding of the relations between hillslope and channel processes. For example, it is generally accepted that channel form is adjusted to the prevailing hydrologic and sediment regime, both of which are largely controlled by the complex interplay between climate, vegetation cover, and the debris contained within the hillslope sediment reservoirs (Ritter et al., 1995). What has only recently been appreciated, however, is that the *history* of hillslope erosion may dictate the nature of the changes in channel form and process that occur in response to either natural or anthropogenic disturbance. Bull (1991), for example, argues that if the geomorphic history of a basin allowed for the significant production of debris within hillslope sediment reservoirs, disturbances such as climate change may lead to widespread slope erosion and concomitant valley floor aggradation; however, if subsequent, but similar disturbances occur prior to the replenishment of the hillslope sediment reservoirs by weathering processes, a completely different set of responses may be initiated, such as channel incision and terrace development. Thus, a sound understanding of geomorphic responses to threshold crossing events not only requires an analysis of the current processes operating within the watershed but the geomorphic history of the basin during the past several hundreds to thousands of years.

Recent studies have also shown that landforms created by hillslope processes (e.g., landslides, debris flow fans, alluvial fans, etc.) may significantly influence both valley floor morphology (width and slope) and the sedimentology of the valley fill, particularly in small, upland drainages (Jarrett and Costa, 1986; Costa, 1988; Carling, 1989; Miller, 1990; Grant and Swanson, 1995; Miller et al., 1999). Valley width and gradient have been shown to influence the erosional capacity of flood flows (Wolman and Eiler, 1958; Kelsey, 1988; Kochel, 1988; Miller et al., 1999), whereas, the particle size and composition of the valley fill largely dictates the erosional resistance of the geologic materials distributed along the axial channels (Schumm, 1977; Grant and Swanson, 1995). It follows, then, that these landforms may have a significant and prolonged effect on the spatial variations in modern channel dynamics, although these effects are only beginning to be conceptually and quantitatively defined.

This paper examines the influence of hillslope processes, and the landforms that result from them, on channel dynamics within upland watersheds of the Great Basin of central Nevada. Axial channels within many of these basins have undergone significant incision during the past several decades; and given the close relationships between plant community type and depths to water tables within the area (Manning et al., 1989; Weixelman et al., 1996; Castelli et al., in review), there is considerable concern that incision may lead to severe degradation of these riparian habitats. Of particular concern are the effects of incision on wet meadow ecosystems that are dispersed along the valley floors. These ecosystems provide habitat for neotropical migrants (Saab and Groves, 1992), a variety of endemics, and a relatively high number of endangered species (Hubbard, 1977). The primary intent of this paper is to demonstrate that modern channel incision, and variations in erosional and depositional processes observed along the valley floor, are directly related to the history of hillslope sediment production and landform development during the mid- to late Holocene.

2. Study area: geologic, hydrologic, and geographic setting

This study focuses on several small (< 100 km^2), upland watersheds within the Great Basin of central

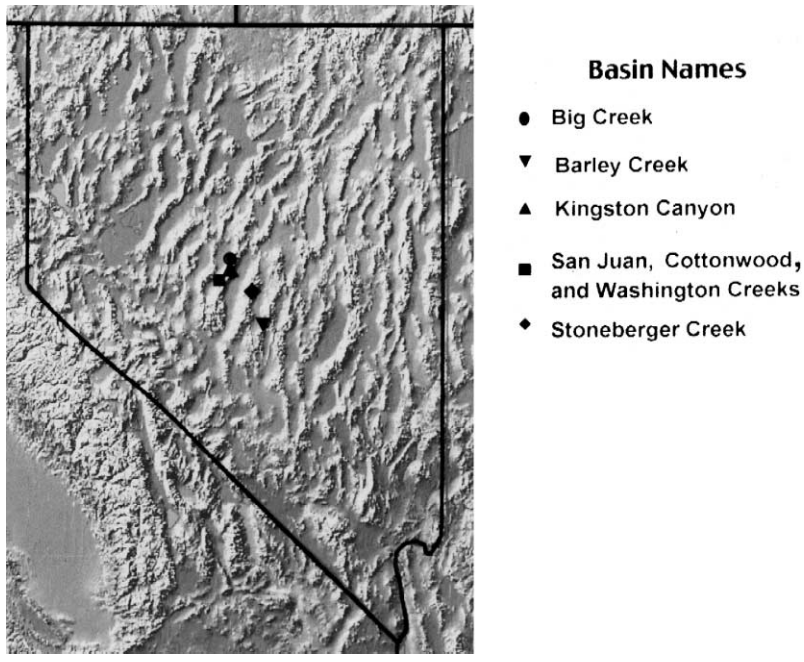

Fig. 1. Location of study basins in central Nevada. Map courtesy of Ray Sterner at http://fermi.jhuapl.edu/states/; north at top.

Nevada, including the San Juan Creek, Cottonwood Creek, Big Creek, Kingston Canyon, and Washington Creek basins within the Toiyabe Range, the Barley Creek basin within the Monitor Range, and the Stoneberger Creek basin within the Toquima Range (Fig. 1). All of these ranges are north–south oriented, fault-blocked ranges characterized by a complex structural geology (Kleinhample and Ziony, 1985). The selected study basins are underlain by different rock types and are believed to reside in range segments characterized by differing rates of tectonic activity (Table 1). Watershed elevations range from about 1850 to 3200 m, with variations in annual precipitation ranging from 20 cm at the basin mouth to 45 cm at upper elevations. Approximately 60% of the precipitation occurs in the form of snow

Table 1
Summary of study basin characteristics

Name	Range name	Basin area (km^2)	Dominant underlying lithologies
Barley Creek	Monitor	92.8	Dominated by undifferentiated ash-flow tuffs with intermediate lava flows at higher elevations
Big Creek	Toiyabe	23.3	Paleozoic chert, shale, quartzite, and greenstone
Cottonwood Creek	Toiyabe	27.9	Dominated by Precambrian and Paleozoic crystalline rocks; Tertiary welded and non-welded tuffs near basin mouth
Kingston Canyon	Toiyabe	60.6	Paleozoic phyllite, shale, limestone; minor amounts of quartzite and chert.
San Juan Creek	Toiyabe	18.7	Tertiary welded and non-welded tuffs; minor amounts of Precambrian and Paleozoic crystalline rocks
Stoneberger Creek	Toquima	92.2	Lower basin (most of basin): chert, siltstone, greenstones, quartzites and tuffs/tuffaceous sed. rocks; upper-most basin: ash-flow tuffs
Washington Creek	Toiyabe	16.5	Paleozoic quartzite and Tertiary granites

during the winter months. Peak runoff results from snowmelt in late May or early June, but localized convective summer storms can result in flash floods. At low to middle elevations, Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis*) communities are interspersed with Utah juniper (*Juniperus osteosperma*) and single leaf pinyon (*Pinus monophylla*) woodlands. At higher elevations, mountain brush vegetation, including mountain big sagebrush (*A. tridentata* spp. *vaseyana*) and limber pine (*P. flexilis*), dominate.

The basins are characterized by an integrated stream system that is incised into low-relief, narrow (< 150 m wide) valley floors. Low flows range from about 0.015 to 0.063 m^3/s, whereas, high flows range from 0.214 to 0.683 m^3/s (Hess and Bohman, 1996). In general, riparian vegetation consists of stringers of quaking aspen (*Populus tremuloides*), narrow leaf cottonwood (*P. angustifolia*), river birch (*Betula occidentalis*), willows (*Salix* spp.), and meadow communities (USDA Forest Service, 1996). At the mouth of the basins, streams flow onto alluvial fans. Small inholdings of private property often exist at this point, and most streams are channelized and diverted to private ranches lower in the broad central valleys.

3. Methodology

The geomorphic history of the study basins was determined by delineating, characterizing, and dating the alluvial stratigraphy of the mid- to late Holocene valley fill exposed within 1- to 5-m high bank exposures found along entrenched channels. The stratigraphic units were subsequently related to valley bottom landforms (e.g., terraces and alluvial fans). Significant effort was placed on (i) defining the relations between hillslope and axial channel deposits and landforms and (ii) relating major erosional and depositional events to paleoclimatic conditions determined using paleoclimate proxy data collected on both a local and regional scale.

The delineation of individual stratigraphic units was based on grain-size distribution, sediment color, clast lithology, degree of sediment weathering, and topographic/stratigraphic position. Once the units had been defined, the stratigraphic sections were mapped in detail to document unit boundary geometry, unit and facies continuity, the location of collected sediment and radiocarbon samples, and the presence of surface or buried soils. The grain size of the > 2-mm sediment fraction was determined using a modified Wolman (1954) approach, and the grain-size distribution of the < 2-mm sediment faction was performed in the laboratory using wet-sieving and pipette techniques modified from Singer and Janitzky (1986). Soil profiles developed in the stratigraphic units were described according to the methods and nomenclature put forth by the Soil Conservation Service (1981) and Birkeland (1984). All radiocarbon analyses were conducted by Beta Analytical, located in Miami, FL. The field and laboratory descriptions of unit sedimentology, the nature of soils developed in the units, and their absolute age were used to correlate the deposits between different locations of the same basin and between basins.

In addition to the data collected above, cross-valley and longitudinal profiles were surveyed within selected watersheds in order to define the topographic relations between the stratigraphic units and to quantify gradient changes along the valley floor, particularly within the vicinity of alluvial fans that had built away from side-valley tributaries. Most surveys were collected using a Leica Total Station; however, in a few localities with extremely dense vegetation, the surveys were conducted using a tape, stadia rod, and abney level.

4. Results

4.1. Overview of valley morphology

Field reconnaissance, combined with detailed topographic surveys, revealed that the study basins and many other upland watersheds within the Toiyabe, Toquima, and Monitor Ranges of central Nevada exhibit similar valley floor morphologies. They are characterized by an integrated stream system that is incised into low-relief, narrow (< 150 m wide) valley floors. Valley widths are locally restricted by bedrock outcrops and, more frequently, alluvial fans that have built away from side-valley tributaries (Fig. 2). In most cases, these side-valley alluvial fans are

Fig. 2. Side-valley alluvial fan within Kingston Canyon which nearly traverses the entire width of the valley floor.

composed of a single, distinct geomorphic surface. Radial fan profiles measured along this surface demonstrate that during aggradational events, many of these fans extended completely across the valley floor, the deposits impinging on the base of the opposing hillslope (Fig. 3). Currently, however, the fan toes are truncated by the axial channel that is now confined between hillslope and distal alluvial fan deposits (Fig. 4). Where truncation has not occurred, the surface of the fan deposits grade smoothly onto the highest surface preserved along the valley floor (which, as will be shown below, corresponds to the surface of Qa2).

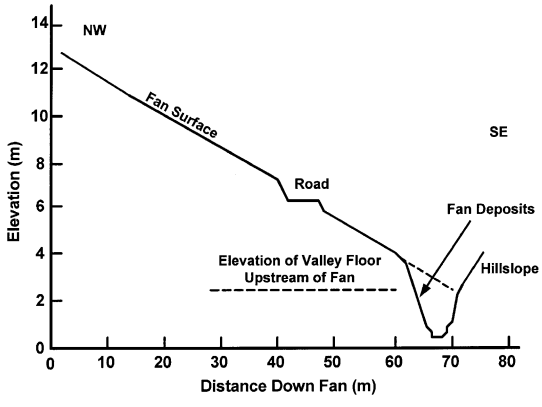

Fig. 3. Radial fan profile of the side-valley alluvial fan as shown in Fig. 2. Prior to the truncation of the fan toe, fan deposits appear to have impinged upon the opposing hillslope.

Examination of axial channel morphology demonstrates that many of the side-valley fans influence stream gradients. Reaches located immediately upvalley of the fans exhibit relatively low gradients. Slopes increase significantly as the channel traverses the fan deposits and then systematically decrease farther downstream, forming a concave-up longitudinal profile between successive fan reaches (Fig. 4). These abrupt changes in gradient lead to significant changes in channel bed and valley floor elevation as the streams cross the fan deposits. For example, the valley floor drops by about 3 m in elevation as the stream traverses the Kingston Canyon fan shown in Fig. 4. The depth of entrenchment also varies along the riparian corridor. Entrenchment is most pronounced at or immediately upstream of the alluvial fans where knickpoints on the order of 1–2 m in height are developed in fan sediments or within axial valley alluvium located immediately upstream (Fig. 4). Moreover, nearly all of the wet meadow ecosystems are found immediately upvalley of alluvial fans that cross the valley floor (although it should be noted that wet meadows are not located upstream of

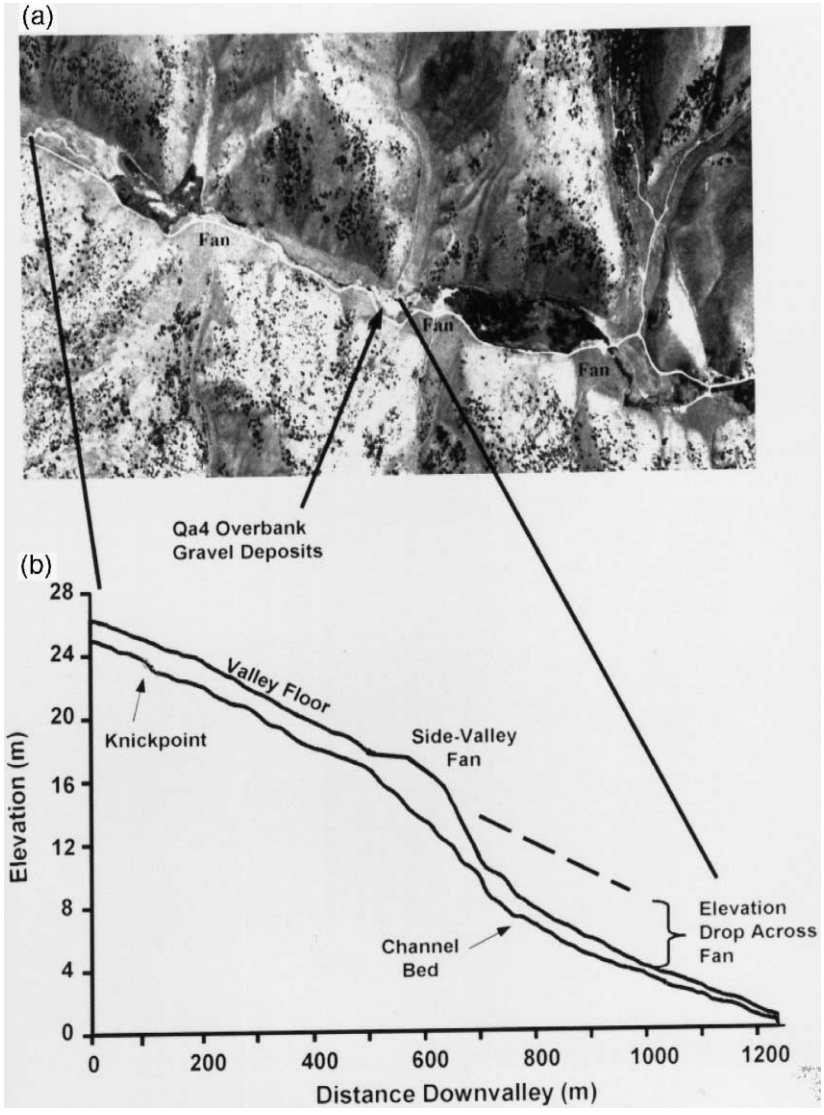

Fig. 4. (a) Aerial photograph of side-valley fans in Kingston Canyon showing variations in valley morphology and vegetation types along the valley floor. (b) Longitudinal profile along the channel bed and valley floor showing the stepped nature of the valley topography.

all side-valley fans). Thus, the depth of incision, the gradients of the channel and valley floor and the nature of the riparian vegetation are directly related to the location of side-valley fan complexes.

4.2. Description of late Holocene stratigraphy

A detailed stratigraphic analysis, consisting of 16 measured sections of the mid- to late Holocene alluvial valley fill, was carried out in the San Juan and Cottonwood Creek basins where numerous 1- to 3-m high bank exposures were present (Waltman et al., 1998). Additional stratigraphic sections were measured within the Barley and Stoneberger Creek basins (Fig. 1). The data indicate that the mid- to late Holocene stratigraphy is similar in all of the upland watersheds that were examined in detail. Moreover,

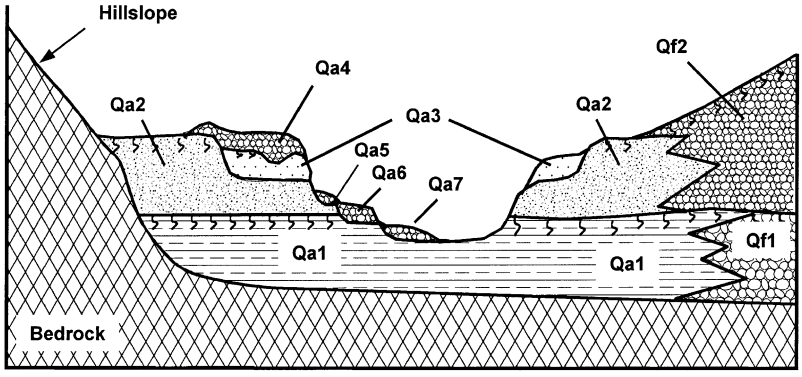

Fig. 5. Schematic diagram of mid- to late Holocene stratigraphy within the study basins.

extensive field reconnaissance suggests that the stratigraphy observed within the study basins is similar to that found throughout most of the upland watersheds of central Nevada, although the areal extent of the individual stratigraphic units, and the magnitude of erosional events as defined by unit size and distribution, varies between the basins.

The late Holocene valley fill consists of four alluvial stratigraphic units that have been named, from oldest to youngest, Quaternary alluvial unit 1 through Quaternary alluvial unit 4 (Qa1–Qa4) and two alluvial fan units (Qf1 and Qf2). In addition, three alluvial units (Qa5–Qa7) occur as inset terraces along the incised channels (Fig. 5).

4.2.1. Axial channel deposits

The oldest alluvial unit, Qa1, consistently occurs at the base of the banks of the incised channels. It is dominated by silt- to fine-sand-sized material that contains varying quantities of pebble-sized gravel dispersed throughout the unit. At all localities, the exposed materials are weathered and a distinct soil profile marks the top of the Qa1 depositional unit (Fig. 6). The nature of the soil profiles varies signifi-

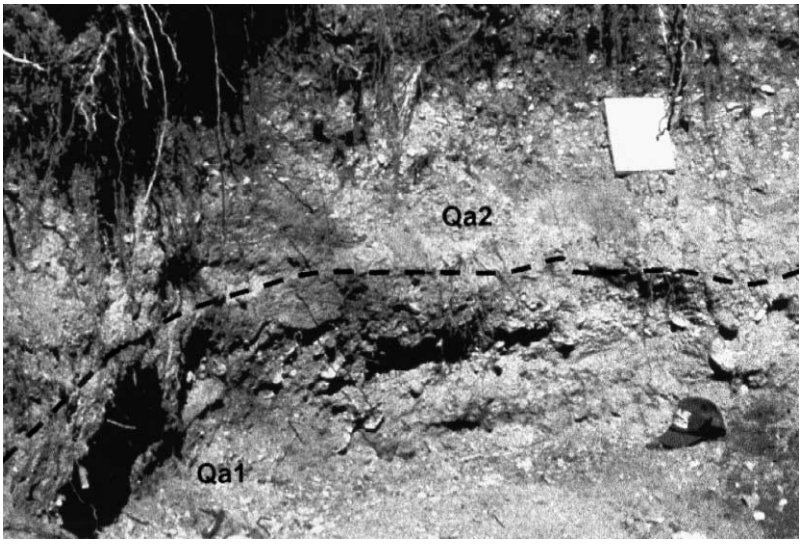

Fig. 6. Soil developed in surface materials of Qa1 deposits within the San Juan Creek basin. The soil is overlain by Qa2.

cantly from site to site. Where Qa1 was described upstream of side-valley alluvial fans, the buried soils are more poorly developed, averaging approximately 15–45 cm in total thickness. However, they exhibit thicker, organic-rich A horizons that locally contain undecomposed plant macrofossils, particularly within the upper few centimeters of the profile. Maximum B horizon development is typically characterized by medium to coarse subangular blocky structure and loam to silt loam textures. In other, better drained locations, profile thicknesses are on the order of 75 cm; and maximum B horizon development is characterized by medium to coarse subangular block structures and sandy clay textures. Radiocarbon dates of charcoal and organic-rich sediments obtained from the Qa1 soils range from 4180 ± 100 to 3450 ± 160 YBP (Table 2).

Qa2 overlies and buries Qa1 (Fig. 5). It is the most extensive alluvial unit, underlying a significant portion of the valley floor within the studied watersheds. Qa2 interfingers with Qf2 deposits (described below) and consists of both fine- and coarse-grained facies. The fine-grained facies ($Qa2_f$) is characterized by silty clay loam textures that contain < 10–15% gravel dispersed throughout the material (Fig. 7). The unit also contains 1- to 10-cm thick, discontinuous layers of dark brown to black silt enriched with charcoal. The coarse-grained facies ($Qa2_g$) is dominated by a clast-supported gravel with a fine sand to sandy loam matrix. This facies typically occurs as 0.5- to 2-m long lenses within the fine-grained facies. The grain size of both facies decrease away from side-valley alluvial fans.

Both the thickness and areal extent of Qa2 tends to increase downvalley. The thickness of Qa2 is on the order of 30- to 150-cm (although it was locally greater in Barley Creek). The near-surface deposits of Qa2 exhibit a soil profile characterized by an approximately 42-cm thick B horizon. Maximum B horizon development is characterized by silt loam

Table 2
Summary of radiocarbon dates obtained on delineated valley fill deposits

Stratigraphic unit (sample number)	Basin	Range	Material dated	Determined age
Qa1				
CW1	Cottonwood Creek	Toiyabe	Bulk Organic Sediment	3450 ± 160
SJ7-B	San Juan Creek	Toiyabe	Charcoal + Organic Sediment	3460 ± 70
SJ5	San Juan Creek	Toiyabe	Charcoal + Organic Sediment	4180 ± 100
Qa2				
BC3-A	Barley Creek	Monitor	Charcoal	1920 ± 60
BC3-B	Barley Creek	Monitor	Charcoal	2040 ± 60
CWJ3	Cottonwood Creek	Toiyabe	Charcoal	1960 ± 50
SJJ4	San Juan Creek	Toiyabe	Charcoal	2130 ± 50
SJ1	San Juan Creek	Toiyabe	Peat	2270 ± 60
SJ5.75A	San Juan Creek	Toiyabe	Bulk Organic Sediment	2580 ± 70
Qf2				
SB3, RC7	Stoneberger Creek	Toquima	Charcoal	2110 ± 40
Qa3				
BC4, RC21	Barley Creek	Monitor	Charcoal	1200 ± 60
SJ3	San Juan Creek	Toiyabe	Bulk Organic Sediment	1250 ± 50
SJJ2	San Juan Creek	Toiyabe	Charcoal	1310 ± 50
Qa4				
SBR2A, RC3	Stoneberger Creek	Toquima	Charcoal	Modern
SBR5b, RC16	Stoneberger Creek	Toquima	Charcoal	440 ± 50
CWJ1	Cottonwood Creek	Toiyabe	Charcoal	210 ± 50
CW5	Cottonwood Creek	Toiyabe	Charcoal	290 ± 50

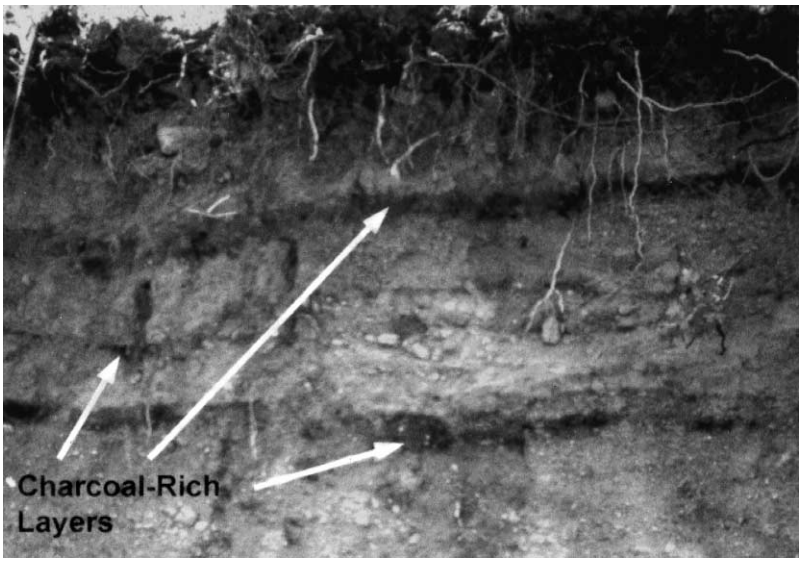

Fig. 7. Qa2 within the San Juan Creek basin. Note the soil profile at surface.

textures and fine subangular blocky structure. Radiocarbon dates obtained on charcoal within Qa2 deposits from the San Juan, Barley, and Cottonwood Creek basins are similar, ranging from 2580 ± 70 to 1920 ± 60 YBP (Table 2).

The areal extent of Qa3 is highly variable along the valley floor within any given basin, and it is not uncommon for it to be locally absent. Qa3 occurs as strath terrace deposits inset into both Qa2–Qf2 materials (Fig. 5). Both a fine- and coarse-grained facies have been delineated in bank exposures (Fig. 8). The fine-grained facies ($Qa3_f$) is typically on the order of 40- to 80-cm thick and consists of silt to sandy loam textures. The coarse-grained facies ($Qa3_g$) contains

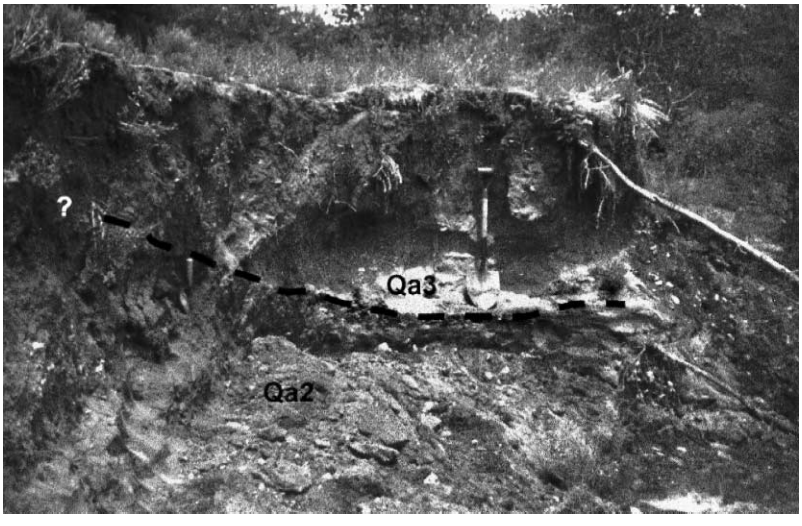

Fig. 8. Qa3 inset terrace deposits along San Juan Creek. Light-colored sediments at base of Qa3 represent coarse-grained facies.

subangular to angular, clast-supported gravels with a sandy loam to fine sand matrix. Locally, the coarse-grained facies exhibits a fining upward sequence ranging from gravel to fine sand (Fig. 8). The surface of Qa3 is characterized by a 15- to 94-cm thick soil, and maximum B horizon development consists of silt loam textures, and fine to coarse subangular blocky structures. Radiocarbon dates obtained on bulk humus and charcoal from Qa3 deposits within the San Juan and Barley Creek basins range from 1310 ± 50 and 1200 ± 60 YBP (Table 2).

Qa4 deposits are geographically limited to reaches of the valley floor immediately upstream of the side-valley alluvial fans and exhibit several depositional styles. The most common Qa4 deposits occur as paleochannel fills that are characterized by poorly sorted sands and silts interlayered with 20- to 40-cm thick peat deposits. Gravel lenses are also present near the base of the paleochannels. The gravels are typically clast supported and contain a sand to sandy loam matrix. Locally, Qa4 occurs as gravel deposits that have spread out over the valley floor (Fig. 9). These deposits are similar to the gravel deposits found within the paleochannel fills and contain a sand to sandy loam matrix. The areal extent of the overbank gravel deposits is highly variable ranging from bars confined to small areas immediately adjacent to the channel to areas where the most of the valley floor has been covered (Fig. 9). Radiocarbon dates obtained on charcoal collected from paleochannel fill deposits range from 440 ± 50 YBP to modern (Table 2). Moreover, Qa4 deposition in both paleochannels and over the valley floor was observed as recently as summer 1998.

4.2.2. Side-valley alluvial fan deposits

Although side-valley alluvial fans are prominent landforms in the study basins, exposures of Qf1 were limited in number as well as in vertical and lateral extent. Qf1 sediment exposures are confined to reaches of the axial channel that had truncated distal fan areas. Qf1 consists of massive, clast-supported, pebble gravels having a variable matrix ranging from clay to medium sandy loam. Within the San Juan drainage basin, soils developed in Qa1 deposits were locally traced onto the surface of Qf1. Profile thicknesses in Qf1 were on the order of 75 cm, and maximum B horizon development was characterized by medium to coarse subangular block structures and clay loam textures.

Descriptions of Qf2 were limited to distal fan areas and were primarily obtained from 1- to 3-m high sections (with the exception of exposures in the Barley Creek basin that locally exceeded 5 m in height). Qf2 primarily consists of massive to weakly bedded, clast-supported gravels containing a loamy, medium to coarse sand matrix. In the distal fan areas, Qf2 overlies Qf1 and interfingers with Qa2

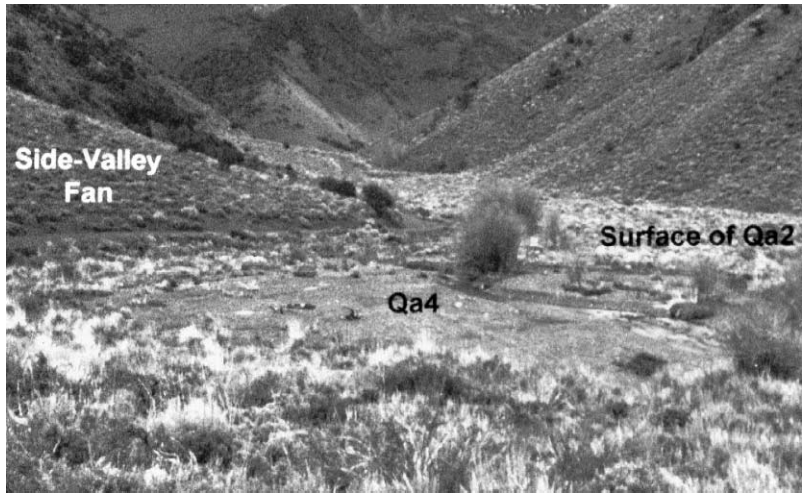

Fig. 9. Qa4 overbank gravel deposits located upstream of a side-valley fan within Kingston Canyon. Qa4 buries Qa2 deposits in this area.

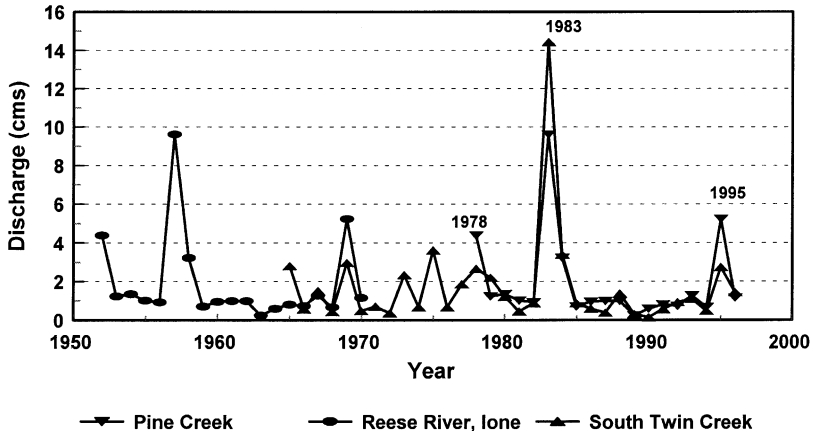

Fig. 10. Discharge measurements at selected USGS gaging stations within central Nevada. Note high flows in 1995, 1983, and the 1970s correspond to periods of Qa5–Qa7 terrace development along the entrenched channels.

deposits (Fig. 5). The Qf2 deposits were generally more poorly sorted and coarser-grained than underlying or overlying Qa2 sediments. A radiocarbon analysis of charcoal collected from Qf2 deposits of Stoneberger Creek dated to 2110 ± 40 YBP (which is similar in age to that of Qa2 deposits). The surface of Qf2 is characterized by a weathering profile that is similar to that described for Qa2 deposits and, at a few sites, soils developed on Qa2 could be traced to the surface of Qf2.

The preservation of soils at the surface of Qf1 and the planar nature of the Qf1–Qf2 boundaries suggest deposition on aggrading fans by episodic, unconfined flows. Thus, we interpret Qf2 to be the product of water floods within low-order, hillslope drainage systems.

4.2.3. Inset terrace deposits

Qa5, Qa6, and Qa7 represent areally restricted units inset within the valley fill (Fig. 5). They are all composed of gravel sized material and are primarily distinguished on the basis of elevation above the modern channel bed. The maximum age of these units has been estimated by dendrochronological dating of willows growing on the surface of the deposits. The ages determined for Qa6 and Qa7 appear to correspond to 1983 and 1995, respectively, both years that were characterized by unusually large amounts of snowmelt runoff (Fig. 10). The ages of willows growing in Qa5 deposits were more variable but appear to cluster in the mid- to late 1970s when several high spring flows occurred.

5. Discussion

5.1. Relations between climate change, hillslope processes, and axial channel responses

Previous investigations in the Basin and Range have found that the style and rates of tectonic activity vary both between ranges and along the piedmonts of any given range (Bull and McFadden, 1977; Wallace, 1987). Wallace (1987), for example, demonstrated that within the Buena Vista valley of central Nevada faults cluster into discrete zones, and that the spatial and temporal grouping of faults may lead to non-uniform slip rates along the mountain front. Inspection of a tectonic map produced by Dohrenwend et al. (1992) reveals that "young" faults within the Toiyabe, Toquima, and Monitor Ranges are also discontinuous. Moreover, mountain front sinuosity, a parameter used by Bull and McFadden (1977) to indicate relative rates of uplift, vary considerably along these range fronts. Thus, it seems likely that the watersheds selected for detailed analysis in this study are characterized by differing rates of tectonic activity.

In spite of existing in different tectonic settings, the stratigraphy and the timing of depositional events are similar within upland watersheds of central

Nevada (Table 2). This suggests that channel processes are responding to regional changes in the environment. In the case of Qa2 and Qa3, the observed alterations in channel form and process predate European settlement, suggesting that the most likely cause for adjustment is climatic change. It follows, then, that the timing of these major geomorphic events should roughly correlate with the timing of climatic alterations documented using climate proxy data from central Nevada.

Numerous studies of Holocene climatic conditions have been conducted within and adjacent to the Great Basin, and they provide a basic understanding of the changes in climate during the past 10,000 years. In addition, climatic and vegetational changes in central Nevada were examined for this study using data from woodrat middens. To date, a total of 18 different strata have been sampled from three woodrat midden locations within the Birch and Big Creek basins (Fig. 1). The midden strata range in age from 100 to 8900 YBP and, together with the modern community, include a total of 236 taxa (Chambers et al., 1998). Interpretation of the woodrat data suggests that the climatic patterns in central Nevada are similar to those deciphered from other climate proxy data from the Great Basin, although minor variations in the timing of the climatic shifts are apparent. The most significant discrepancy is in the timing of the Neoglacial. Regional studies suggest that cool, moist conditions associated with the Neoglacial continued until approximately 2000 YBP, whereas the local data show that a decline in the diversity of hillslope plant species had clearly begun by 2500 YBP (Fig. 11). Both regional and local data show that the Neoglacial was followed by a significant drought and, given the temporal and spatial variability associated with climate change processes, it is not surprising that minor variations in the timing of climatic shifts are apparent on a local scale.

In general, erosional and depositional events observed within the upland basins closely parallel major shifts in climatic regime and vegetation cover (Fig. 11). Radiocarbon dates obtained from the oldest unit (Qa1) range in age from 4180 to 3450 YBP and correspond to the Neoglacial (approximately 4500–2500 YBP in this area). The Neoglacial was characterized by relatively cool and wet climatic conditions (Wigand, 1987) during which the upper tree line lowered in elevation in the White Mountains (LaMarche, 1973) and the Sierra Nevada. Within the study area, the Neoglacial exhibited a relatively high number of plant taxa (Fig. 11). The radiocarbon dates from Qa1 samples were obtained on charcoal and organic-rich sediments found within buried soil A horizons. Thus, the valley floors by approximately 4200 YBP were characterized by an

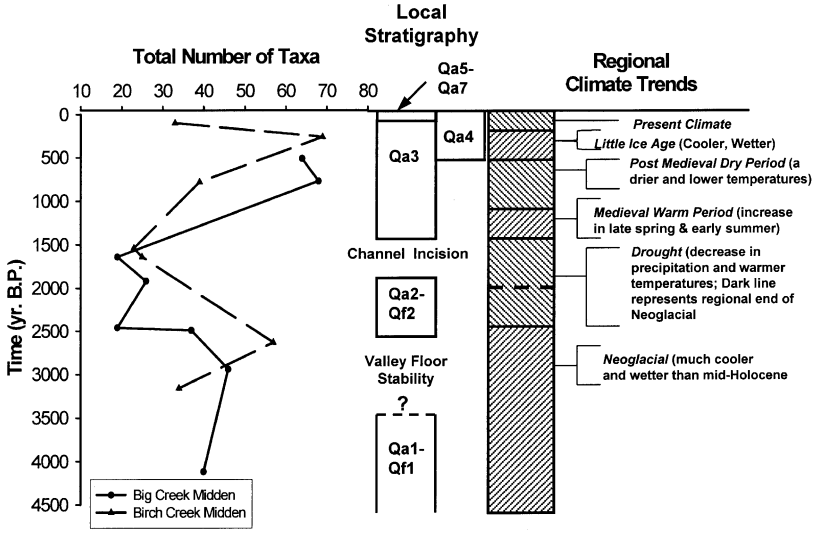

Fig. 11. Relations between alluvial stratigraphic units delineated in central Nevada and the timing of climatic shifts.

episode of soil development and the local accumulation of organic materials and were apparently stable. While the exact nature of the valley bottom topography during this interval cannot be determined, Qf1 is buried beneath distal Qf2 deposits, indicating that side-valley fans existed in the upland drainages and restricted valley floor widths. Moreover, the occurrence of organic-rich, peat-like deposits upvalley of Qf1 fans suggests that wet meadow complexes may also have occurred upstream of the alluvial fans, much as they do today.

Qa2 buries Qa1 and underlies most of the valley floor in these upland watersheds. The interfingering relationship between Qa2 and Qf2 indicates that they were syndepositional. Radiocarbon analysis of charcoal constrain the age of Qa2–Qf2 from approximately 1920–2580 YBP. Paleoecological studies have shown that at approximately 2500 YBP, there was onset of a severe drought, characterized by warming temperatures, that resulted in a decrease in woodlands and an increase in dominance of desert shrub vegetation throughout the northern Great Basin (Wigand et al., 1995). Locally, data from woodrat middens demonstrate that the total number of upland plant taxa dropped by 50% or more within and adjacent to the study basins (Fig. 11). Thus, it appears that the initiation of hillslope erosion, fan building, and valley deposition was associated with a climatic shift from moister to drier conditions and a significant change in the nature of the upland vegetation.

Previous studies in arid climatic regimes have also recognized periods of increased hillslope erosion resulting from a change to drier, warmer conditions (Bull and Schick, 1979; Wells et al., 1987; Ritter et al., in press). These observations led Bull and Schick (1979) to develop a process-response model to explain the relationship between increased sediment yield and decreasing effective precipitation. The model is based on the assumption that hillslope sediment availability and erosion are enhanced by a decline in vegetation and subsurface root densities. They argue that minor changes in climate can result in a significant change in sediment loads to fans and axial channels, allowing aggradation to occur. Wells et al. (1987) modified the Bull and Schick model by arguing that increased runoff could also result from decreases in the infiltration capacity of the hillslope soils. In the case of the Mojave Desert where their study was conducted, they suggested that the deposition of fine-grained, eolian sediment and salt increased rates of hillslope pedogenesis and decreased infiltration capacities of the soils. The net effect was increased runoff from the less permeable hillslopes that when combined with increased sediment availability associated with the decline in vegetation density, resulted in fan aggradation in spite of increasing aridity.

We envision a model similar to that first proposed by Bull and Schick (1979) and later modified by Wells et al. (1987) in which a decline in vegetation density caused by a shift to drier, warmer conditions increased runoff and hillslope erosion. The change in sediment and water production initiated an episode of side-valley alluvial fan building and aggradation within the valley bottoms represented by Qa2–Qf2 deposits. An abundance of charcoal occurring in multiple, thin but distinct layers within Qa2 suggests that numerous wildfires may have occurred during this post-Neoglacial drought. It seems likely that these fires would have increased hillslope sediment availability and runoff, exacerbating aggradation at the base of the slopes.

Data from local woodrat middens and other climate proxy indicators from the Great Basin suggest that the drought conditions lasted until about 1300 YBP (Fig. 11). However, radiocarbon dates of charcoal collected from Qa2–Qf2 deposits in four separate watersheds reveal that fan building and valley aggradation declined dramatically after approximately 1900 YBP (Table 2). Moreover, Qa3 deposits are inset into units Qa2–Qf2 indicating that the aggradational episode was followed by a period of minor entrenchment that pre-dated the deposition of Qa3. Bull (1991) has argued that aggradational and erosional processes can be significantly affected by changes in the availability of sediment on the hillslopes during an erosional event. Application of this argument to the upland basins of central Nevada suggests that minor valley entrenchment following the deposition of Qa2–Qf2 may have occurred during drought conditions as hillslope sediment reservoirs were depleted. Although bedrock outcrops are extensive on the hillslopes of these upland drainages, large amounts of sediment are also locally present. Where these sediments occur, they are often charac-

terized by a thin surface mantle consisting of coarser debris than is found at depth, a stratigraphic relation that is suggestive of past erosional processes. We hypothesize that during Qa2–Qf2 deposition finer-grained sediments were preferentially removed from the slopes, producing this coarse-grained surface lag. This is supported by the fact that Qa2 tends to be finer grained than subsequently deposited stratigraphic units including Qa3–Qa7. This hillslope winnowing process would presumably have increased the infiltration capacities of the soils, reduced overland flow, and decreased sediment loads to fan and axial stream systems. Although the runoff within the basins may have decreased, the sediment-deficient nature of the flows would presumably have initiated channel incision (Fig. 12). The significance of this hypothesis is that two opposing geomorphic responses may have been produced from a single shift in climatic regime as a result of physical changes within the hillslope system. The initial response was massive aggradation, whereas the final response was channel incision. Moreover, it implies that channel processes operating over time scales of years to decades are strongly influenced by changes in hillslope processes that operate over hundreds of years.

Radiocarbon dates from the base of Qa3 deposits range from 1310 to 1200 YBP, suggesting that Qa3 deposition was associated with the onset of the Medievil Warm Period. The Medieval Warm Period (1300–900 YBP) was characterized by even warmer temperatures than previously existed and a seasonal shift in precipitation with a greater quantity and proportion falling in early summer. Milder winters reduced snowpack, and lower lake levels were evident (Born, 1972). Locally, the total number of plant taxa is thought to have begun to increase in upland areas (Fig. 11).

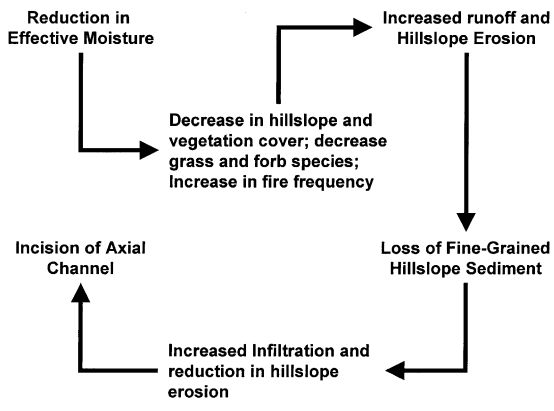

Fig. 12. Relations between climate and vegetation change, hillslope processes, and axial channel response between approximately 2500–1900 YBP in upland watersheds of central Nevada.

Given that Qa3 is associated with strath terraces created by lateral planation, it appears that channel and valley floor systems were relatively stable at this time. Moreover, aggradation on the side-valley fans has been extremely limited since the cessation of Qf2 deposition at approximately 1900 YBP. The deposition of Qa3 is thought to have continued until the onset of the most recent phase of channel incision, which may have began in the late 1800s, or more recently, in some watersheds. However, radiocarbon dates on samples collected from Qa4 indicate that localized episodes of cutting and filling upstream of the side-valley fans began approximately 440 YBP (Table 2) and continues to the present. Thus, the deposition of Qa3 and Qa4 deposits has been contemporaneous during the past several centuries but spatially separated.

The relations between climate change and Qa4 deposition are uncertain, but Qa4 deposition possibly began with the onset of the Little Ice Age (500–150 YBP), which was characterized by a cool, wet climatic regime and an abundance of vegetation. A more detailed description of the processes of Qa4 deposition are presented below. What is important to recognize here is that the incision that produced the paleochannels filled by Qa4 deposits are highly localized, occurring only upstream of the side-valley fans. In contrast, channel entrenchment associated with Qa5–Qa7 occurred along the entire drainage of many, if not most, watersheds in the area, although the magnitude of incision is variable. The dendrochronologic data collected from willows growing on these terraces demonstrate that they were created by downcutting associated with major floods. Presumably, modern entrenchment of the axial channels is driven by sediment deficient, high magnitude flows that primarily occur during the spring snowmelt.

Channel degradation has been described throughout the western US during historic times and has most often been attributed to anthropogenic influences including overgrazing, changes in fire frequencies due to fire suppression, mining, recreational

activities, wood-gathering, and road construction (Gifford and Hawkins, 1978; Caldwell et al., 1981; Johnson, 1992; Miller and Wigand, 1994; Trimble and Mendel, 1995). However, data presented here, as well as in other studies (e.g., Hereford, 1984; Balling and Wells, 1990; Chatters and Hoover, 1992; McFadden and McAuliffe, 1997; Chambers et al., 1998) illustrate that channel degradation may also result from climate change and its influences on vegetation, runoff, and sediment yields. The degree to which each of these groups of disturbances is responsible for channel degradation has become a significant topic of debate, and the separation of the role of natural and anthropogenic disturbances on channel dynamics has become a fundamental question in geomorphology.

Several factors make it impossible to accurately determine the role of natural and anthropogenic disturbances in initiating the most recent phase of channel entrenchment within the upland drainages examined here. These factors include (i) a lack of understanding of the land-use changes that have occurred within the study basins and (ii) an inability to precisely constrain the timing of incision during the past 150 years and their relations to historic shifts in climate. What is important to recognize, however, is that channel incision has been the primary geomorphic response within these watersheds for approximately the past 1900 years, while there is no evidence to suggest that significant episodes of hillslope erosion have occurred. This is true even for basins in which the upland vegetation has been severely degraded. For example, Germanoski and Miller (1995) examined the geomorphic responses of the Crow Canyon watershed, located within the Toiyabe Range near Austin, NV, to a wildfire that occurred in 1981. The fire resulted in the complete destruction of all ground and tree foliage, leaving only charred trunks and branches. In spite of the fact that the largest precipitation and runoff events of the past century occurred in 1983, they found that hillslope erosion following the fire was limited. The primary geomorphic response was axial channel entrenchment that reached as much as 3.9 m in depth. Although the Crow Canyon basin is underlain by coarse-grained granodiorites and quartz monzonites that would not be expected to produce large quantities of fine sediment, the data collected by Germanoski and Miller (1995) demonstrates that only limited hillslope erosion can be initiated in many watersheds throughout this area under the current hydrologic regime.

The significance of the above observations is that the evolutionary history of the upland watersheds in central Nevada during the late Holocene appears to have produced hillslopes with only a limited amount of debris that can be removed from the sediment reservoirs. Thus, the axial channels are inherently prone to incision. Any disturbance that leads to increased runoff, regardless of whether it is due to natural or anthropogenic processes, is most likely to produce entrenched axial channels.

5.2. Influence of side-valley alluvial fans on axial channel stability

The longitudinal, axial channel profiles within the upland basins are characterized by a “stepped” geometry in which significant changes in channel and valley floor elevation periodically occur over a relatively short, downvalley distance (Fig. 4). Each of these steps correspond to a reach that traverses the toe of a side-valley fan characterized by a radial profile which indicates that it once extended across the entire width of the valley floor. The cause(s) for the stepped longitudinal valley profiles are not entirely clear. It is possible that these steps locally correlate with normal faults that traverse the valley floors, perpendicular to the axial channel, with the upthrown blocks positioned on the upvalley side of the steps. In this case, the coexistence of fans and faults may be related to the development of drainage systems along fault traces characterized by fractured and erosionally less resistant bedrock. The inspection of local geologic maps combined with field observations have shown that valley “steps” do, in some cases, correspond to normal faults. However, there is no evidence to suggest that this is true in all, or even in most, cases. An alternative explanation is that during Qa2–Qf2 time, the nature of hillslope sediment delivery to the axial valley resulted in a spatially asynchronous pattern of sedimentation along the valley floor that ultimately produced the stepped-channel profile. Stratigraphic interfingering of Qa2 and Qf2 deposits along with radiocarbon dates indicate that fan and valley fill sedimentation

were contemporaneous. Moreover, the prominence of side-valley alluvial fans indicates that the valley-side tributaries were major sources of sediment to the axial system. The episodic delivery of sediment from the valley-side tributaries would have resulted in fan progradation into and across the valley floor as illustrated by the radial fan profiles. The deposition of these fan deposits would have also facilitated sedimentation upstream of the fans by reducing axial channel gradients and restricting flow and would have eventually resulted in the observed longitudinal profile.

As noted above, incision is a significant, basin-wide process that is currently underway in nearly all of the watersheds examined in central Nevada. However, the magnitude of incision is not uniformly distributed along the axial channels but varies as a function of distance from side-valley alluvial fans that create the stepped longitudinal valley profiles. The most significant cutting is located along the channel where it traverses the toe of the side-valley fans and immediately upstream of these fan units within wet meadow complexes.

It is generally accepted that "smooth" concave-up longitudinal profiles represent the equilibrium form in alluvial channels (Leopold et al., 1964). The departure of the longitudinal profiles from a concave-up form for the upland streams examined here is presumably responsible for the localized instabilities, the local increase in the magnitude of incision occurring in an attempt to remove the observed "steps". Thus, the alluvial fans are acting as local base-level controls that dictate the local rates of upstream entrenchment through the wet meadow complexes. It appears that these controls have been in existence for at least the last 1900 years. The prolonged existence of the features appears to be related to two factors. First, the side-valley fans are breached at the lowest point in the valley topography, which occurs along the contact between the fan deposits and the opposing hillslope. As a result, the channel is often underlain by highly resistant bedrock.

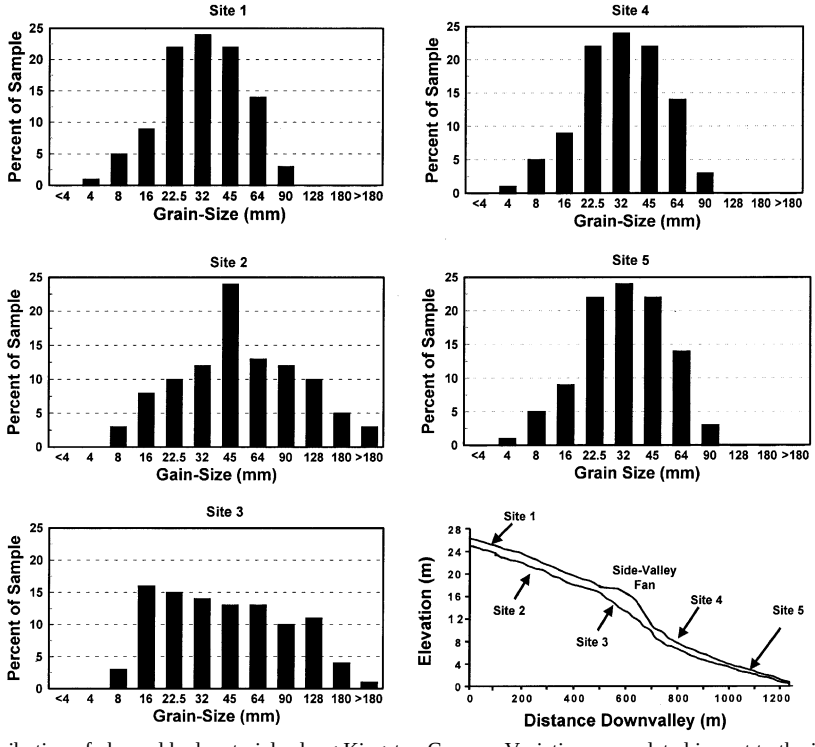

Fig. 13. Grain-size distribution of channel bed materials along Kingston Canyon. Variations are related in part to the influx of sediment from the coarse-grained side-valley alluvial fans.

Second, debris eroded from the fan deposits and incorporated into the channel bed tends to be coarser grained and more poorly sorted than the sediments found either up- or downstream of the fans (Fig. 13). The coarse-grained nature of these reaches presumably reduces the rate at which erosion can occur under the current hydrologic regime.

While incision is the dominant process along the axial streams, the relatively recent deposition of Qa4 sediments in paleochannels and as overbank deposits has periodically occurred immediately upstream of the alluvial fans. It appears that Qa4 aggradation is a temporary phenomenon that is primarily related to the instantaneous influx of sediment to an otherwise sediment-starved channel. For example, a recent episode of channel filling occurred along Cottonwood Creek in 1983, immediately upstream of a side-valley alluvial fan that extends across the valley floor. Deposition was probably enhanced by (i) a decrease in channel gradient in this area and (ii) a bottleneck effect, where water and sediment was temporarily ponded due to the dramatic changes in valley width as flood flows approached the side-valley fan. The ultimate product of channel aggradation was the formation of Qa4 overbank gravel deposits and the cutting of a new channel into older Qa4 deposits in an entirely different location as floodwaters spread out across the valley floor. Field observations revealed that the source of the debris was sediments that had accumulated behind a series of upstream beaver dams. These sediments were eroded when the dams were breached by spring flood waters. Other recent Qa4 deposits have been related to the reworking of mass movements following their occurrence in the area and the localized upstream incision of valley fill deposits.

Radiocarbon dates obtained on Qa4 deposits preserved within bank exposures suggest that the alteration of aggradation and erosion have been ongoing processes for at least the past 440 years. Given that the alluvial fans are acting as local base-level controls, and that localized incision and deposition are significantly influenced by the stepped longitudinal configuration of the valley floors, then some stream reaches are inherently unstable. Moreover, the instability is the direct result of the depositional patterns within the valley bottoms that occurred approximately 1900 years ago.

6. Conclusions

Geomorphic, stratigraphic, and paleoecological data collected in upland watersheds of central Nevada demonstrate that a single climatic shift to warmer, drier conditions at approximately 2500 YBP led to two contrasting geomorphic responses. The initial response occurred when hillslope sediment reservoirs contained an abundance of fine-grained debris and was associated with a decline in vegetation that resulted in the erosion of both fine- and coarse-grained sediments from hillslopes. Slope erosion led to valley aggradation as the debris was transported to side-valley alluvial fans and the axial channel systems. However, the removal of fine-grained materials from the slopes appears to have altered the complex interplay between hillslope soils, infiltration, runoff, and sediment yields in such a way as to have eventually decreased slope erosion. The net result was the cessation of fan building and the onset of axial channel incision. Although the magnitude of incision has been variable within and between basins, channel entrenchment has continued to be the primary geomorphic response within these watersheds since the cessation of channel and valley floor aggradation approximately 1900 years ago. It is hypothesized that these basins will be prone to channel entrenchment until fine-grained sediments accumulate within the hillslope sediment reservoirs, a process that may require several thousands of years to occur (Bull, 1991).

Variations in the distribution of Qa4 deposits and the magnitude of modern channel entrenchment suggest that valley bottom landforms created by hillslope processes (i.e., side-valley alluvial fans) exert a significant control on the spatial distribution of channel processes. Moreover, within the upland basins of central Nevada, these influences have persisted for the past several millennia.

Most restoration and management strategies that are currently utilized along axial channel systems do not consider the potential, long-term influences of hillslope processes on modern channel dynamics. The data collected here illustrate that the evolutionary history of hillslopes can significantly influence channel form and process as well as the geomorphic responses to either natural or anthropogenic disturbances over time frames ranging from centuries to

millennia. Thus, the development of sound restoration and management strategies must not only be based on an understanding of the process linkages between hillslope and channel systems but on the potential influences of the evolutionary history of slope processes and the landforms that they create on modern channel dynamics.

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