A reduced relevance of vegetation change for alluvial aggradation in arid zones

Jose Luis Antinao* and Eric McDonald
Division of Earth and Ecosystem Sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, Nevada 89512, USA

ABSTRACT

A basic tenet of arid region geomorphology is that a decrease in hillslope vegetation density coupled with increases in monsoonal precipitation after a change to a warmer and drier climate is an essential factor for an increase in sediment yield and fan aggradation. Over the last two decades vegetative cover change is increasingly cited as a prominent factor in triggering the onset of fan aggradation in deserts of southwestern North America, especially in analysis of fan deposition during the late Pleistocene–Holocene (LPH) climatic transition. To assess this assertion, we compiled paleobotanical and alluvial fan stratigraphy histories from 18 published studies broadly representing four different areas in the Mojave and northern Sonoran Deserts. Instead of focusing on chronology aggregation and comparison with global or regional climate change proxies forced by orbital parameters, we discriminated by altitudinal regions, looking for linkages between local vegetation change and alluvial deposition. Results indicate that the onset of extensive alluvial fan deposition (1) began well before changes in catchment vegetative cover, and (2) can occur during several possible combinations of vegetation change. The ambiguous relation between vegetation change and alluvial fan aggradation indicates that vegetation had a reduced role in LPH aggradation. Other factors, such as local storm intensity and water and sediment redistribution pathways on hillslopes, need to be considered in this analysis given the important role that the combined hillslope/alluvial system has on arid region ecosystem functions.

INTRODUCTION

Bull (1991) proposed one of the most cited models of alluvial fan aggradation for North American deserts, hypothesizing (1) increased production of hillslope regolith during periods of cooler and wetter climate, (2) increased runoff, hillslope sediment yield, and fan aggradation during the transition to dry periods caused by a reduction in canopy cover or plant density coupled with increased high-intensity convective storms, and (3) subsequent incision and abandonment of fan surfaces once higher runoff has removed most of the soil cover, exposing bedrock (Fig. 1). Glacial-interglacial cycles were used to explain moisture source variability affecting vegetation on hillslopes (Bull, 1991), specifically changes from woodland and shrublands into scrublands and bare desert slopes after a transition to dry periods.

The aforementioned model has provided a powerful conceptual framework to study alluvial fan histories, especially fans generated during the late Pleistocene–Holocene (LPH) in southwestern North America, as well as other desert regions. Over time, decreasing vegetative cover has received greater emphasis as the stated reason for the onset of aggradation (Harvey et al., 1999; Reheis et al., 1996, 2005; Spelz et al., 2008; Miller et al., 2010), raising two important issues. First, the original model (Bull, 1991) was based on limited ages for alluvial aggradation and on paleoclimate data provided mainly by a limited number of discrete vegetation proxy records of packrat middens. Since then, a large amount of data has been published regarding LPH alluvial fan deposition (e.g., Miller et al., 2010) and compositional changes in vegetation (Koehler et al., 2005; Strickland et al., 2005), and a regional synthesis of these expanded data sets to assess the relative timing of alluvial fan aggradation onset compared to vegetation change is still lacking. Second, the application of this model to fans of other ages or in other arid regions (e.g., the Middle East) has not demonstrated linkages between climatic transition, vegetation change, and landscape response similar to those originally inferred for the North American deserts (Enzel et al., 2012). In some catchments of the Mojave and Sonoran Deserts, alluvial fan aggradation has been recorded during all possible (orbital-scale) climate change scenarios (Spelz et al., 2008; Miller et al., 2010; Sohn et al., 2007; Armstrong et al., 2010), including the late Holocene onset of stronger global El Niño–Southern Oscillation (ENSO) events (McDonald et al., 2003; Mahan et al., 2007). This suggests that the local expression of regional climate patterns, even those developed entirely during a relatively dry and warm interglacial, may have a larger relevance for local sediment transport than the variability in vegetation broadly associated with global glacial cyclicity and its effects on precipitation and discharge.

Our objective is to use a regional analysis of alluvial fan and paleobotanical histories to evaluate the premise that alluvial sedimentation should occur primarily after a considerable decrease in vegetation cover (Bull, 1991). This hypothetical response should be clearly observed when comparing alluvial deposition and concurrent vegetation change in multiple catchments across a desert region. Our results, discussed below, suggest that this linkage is tenuous and that the effects of vegetation change on the onset of sediment detachment and transport display sufficient variability to question their prominent incorporation into a general model for alluvial fan aggradation in arid regions.

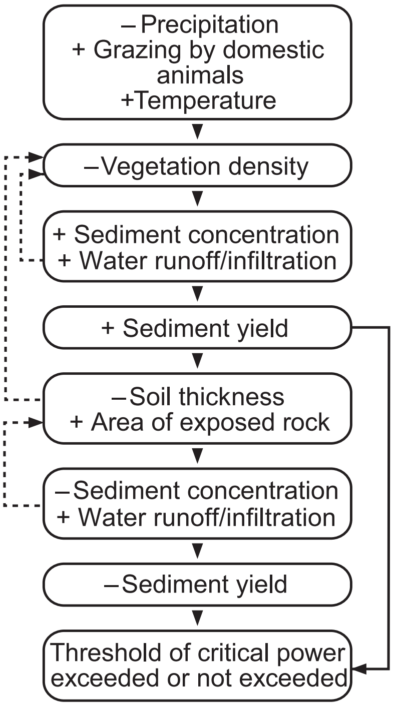

Figure 1. General flow diagram showing increase (+) and decrease (–) of variables involved in sediment transport processes on hillslopes and resulting alluvial fan aggradation in the deserts of the southwestern United States (after Bull, 1991, p. 115). Feedback pathways are indicated by dashed flow lines.

METHODS

We compiled data from 18 published studies of paleobotanical and alluvial fan stratigraphy broadly representing four different areas in the Mojave and northern Sonoran Deserts to examine relations between the timing of vegetation change and fan aggradation onset (Fig. 2;

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*E-mail: jantinao@dri.edu.

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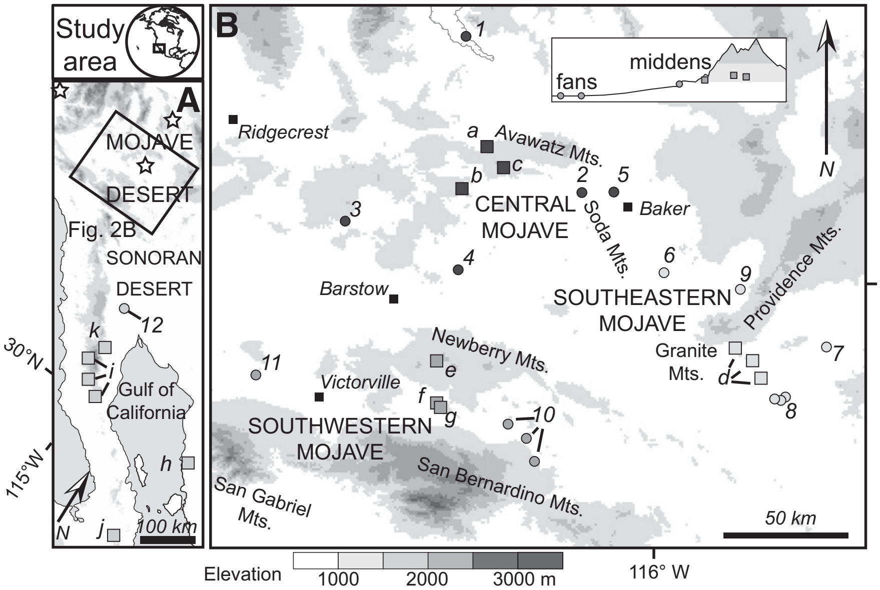

Figure 2. Location of study area. Numbered circles correspond to alluvial record sites. Labeled squares (a–h) represent midden sites (Table DR1 [see footnote 1]), adding Cataviña/Velicatá (i), Sierra San Francisco (j), and Sierra San Pedro (k) sites in Baja California, Mexico, that follow the general trend of final upslope movement of woodlands during the late Pleistocene–Holocene, but that are not discussed in the text because they lack alluvial data in the vicinity. References for all sites are given in the Data Repository (see footnote 1). A: Study area in a broader view of southern California and northern Baja California, showing the spatial relation between the Mojave and Sonoran Deserts. Stars denote location of Mojave and southern California lacustrine and groundwater-discharge records (Harvey et al., 1999; Quade et al., 1998; Negrini et al., 2006) that are discussed in the text. B: Location of midden and alluvial chronology records. Inset shows altitudinal distribution of sites in the central Mojave subregion, as an example.

Table DR1 in the GSA Data Repository[1]). We grouped data sets displaying vegetation change in altitudinal zones where sediment generation is expected to have fed alluvial deposition downstream during approximately the same period. Timing of aggradation is constrained by chronological data from within sedimentary units, excluding minimum or maximum ages (Spelz et al., 2008; Miller et al., 2010; Mahan et al., 2007; Sohn et al., 2007; Armstrong et al., 2010; Clarke, 1994; Rockwell et al., 2000). Implicit in our analysis is the commonly used assumption (cf. Bull, 1991) that compositional changes can be used as proxy for changes in quantitative plant density or canopy cover.

RESULTS: THE RELATIVE TIMING OF VEGETATION CHANGE AND ALLUVIAL DEPOSITION

Analysis of the compiled data for the different sites in the Mojave and Sonoran Deserts does not support the tenet that a decrease in vegetative cover by the arrival of more arid vegetation types is a major factor in triggering alluvial aggradation (Fig. 3). Aggradation developed earlier across a wide range of elevations and vegetation cover in all areas, including elevation ranges withstanding the more dramatic vegetation change (e.g., Providence Mountains, California), as well as those at lower (e.g., Sierra Mayor, Mexico) and higher (e.g., San Bernardino Mountains, California) elevations. In all areas in the Mojave, alluvial deposition started well before the change from the late Pleistocene woodlands to the Holocene desert scrub (Figs. 3A–3C). Onset of aggradation predates by 2000 yr or more the interpreted timing for change from woodland to scrub. In other words, aggradation started during an apparent dominance of pinyon-juniper types in the hillslopes. In the southeastern Mojave (Fig. 3B), aggradation began under a scrubland cover and appears to have continued through a short phase of juniper establishment in the hillslopes.

In the low-elevation Sonoran Desert (Fig. 3D), aggradation also began well before development of a more arid vegetation cover. Boojum tree (*Fouquieria columnaris*) associations that depend on winter precipitation in this region are an analog to the presence of juniper woodlands at lower altitudes in the Mojave, and therefore ecotone shifting in the Sonoran catchments can be associated with the arrival of desert scrub to the hillslopes. Similarly to the Mojave sites, aggradation started at least 4000–5000 yr before the ecotone shift.

DISCUSSION: ASSESSING LIMITATIONS OF VEGETATION CHANGE AS A PRINCIPAL TRIGGER IN FAN DEPOSITION

Compositional changes in vegetation (Fig. 3) mainly occurred well after the onset of LPH alluvial fan aggradation, indicating that vegetation probably had a moderated role in triggering it relative to other factors such as changes in synoptic weather patterns and the surface hydrology of catchments.

Short-term studies also suggest that vegetation is not the only factor that controls hydrologic responses on catchment hillslopes. In these studies, change from woodlands to shrublands or desert scrub does not cause changes in runoff, erosion, and ultimately aggradation (Pierson et al., 2007), as opposed to studies analyzing effects from decreased plant canopy in shrubland or grassland communities (Abrahams and Parsons, 1991; Parsons et al., 2009). Runoff generation and sediment supply from hillslopes can also be affected by properties such as stone cover, surface sealing, colluvium depth, and underlying bedrock weathering or fracture density (Parsons et al., 2009; Kuhn and Yair, 2004). Although the effects of stone cover on infiltration are complex, surface runoff generally decreases when stone cover increases due to an increase in surface roughness (Yair and Klein, 1973). Stone cover not only decreases overland flow velocities, runoff, and soil detachment, but also increases protection of soil structures against aggregate breakdown and surface sealing by raindrop impact (Abrahams and Parsons, 1991; Parsons et al., 2009). Most mid-elevation (~1000 m) hillslopes across the Mojave and Sonoran Deserts today display soils formed in coarse colluvial mantles (McDonald et al., 2003; Hunt and Wu, 2004) derived from highly fractured bedrock. In these regions surface runoff and sediment transport from vegetation-poor and exposed colluvium is limited except under very high-intensity rainfall on hillslopes, an effect demonstrated for the Negev (Kuhn and Yair, 2004) and southwestern North America (Reid et al., 1999), with enhanced sediment yield documented independently of vegetation cover type.

The spatial distribution and stand density of the woodlands during the LPH would also have a variable effect on runoff and erosion depending on the way they evolved into desert scrub areas with an increase in aridity. If Mojave Pleistocene woodlands were open, with intercanopy shrubs and grasses, similar to the ones present today in the central Great Basin or the Colorado Plateau (Romme et al., 2003), progressive upward ecotone shift was probably accomplished first by replacement of pinyon with juniper (Allen

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[1] GSA Data Repository item 2013001, supplementary information on methods, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

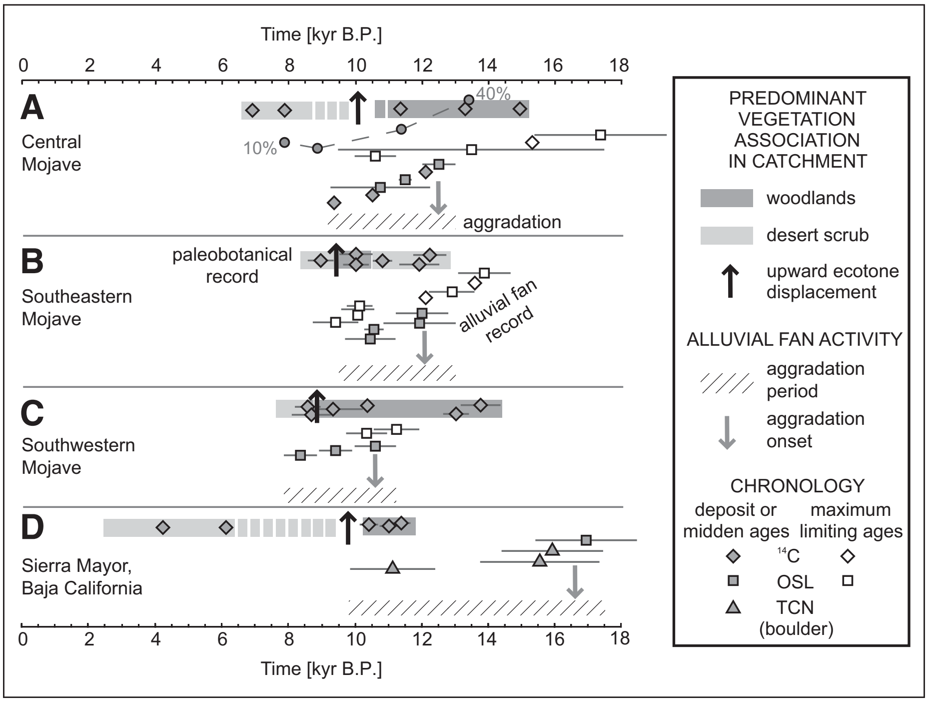

Figure 3. Comparison of alluvial fan aggradation with vegetation changes during the late Pleistocene–Holocene transition in the Mojave and Sonoran Deserts and with nearby climate and vegetation records for central Mojave (A), southeastern Mojave (B), southwestern Mojave (C), and northern Sonoran (D). Note that the term woodland vegetation comprises juniper associations in the Mojave sites and boojum tree (*Fouquieria columnaris*) associations in the Sonoran, low-elevation sites. Ages obtained from embedded remains or layers in the deposits (filled symbols) are a more robust indication of the period of deposition than bracketing ages (open symbols), and were used to constrain aggradation start (gray arrows) and duration (cross-hatched bars). All vegetation analyses correspond to macrofossil remains, except for the NN Basin (Koehler et al., 2005), with *Juniper* sp. Percent pollen data plotted as filled circles. All quoted uncertainty is 1σ, except for terrestrial cosmogenic nuclide data at 2σ. Details on methodology and references for all sites are given in the Data Repository (see footnote 1).

and Breshears, 1998) and then by progressive replacement with shrubs and grasses, not by an immediate conversion to shrubland with greatly reduced cover. Rapid transformation of juniper open stands into sparse shrub cover could have caused an increase in runoff and sediment yield only if shrub cover decreased to less than 20% (Buis et al., 2010). There is no indication, however, that this happened before aggradation started in the studied catchment groups (Fig. 3). Dense pinyon-juniper forests, which may yield a larger reduction in canopy cover upon their demise, normally thrive in shallow, rocky soils (Romme et al., 2003), which display low surface runoff even when they have limited vegetation cover due to the stone-cover effect (Parsons et al., 2009). Thin rocky soils also may have supported the replacement of juniper stands with a shrub cover in the intercanopy area so that the cover density was maintained. Sparse woodland stands can also maintain their productivity and retain canopy cover with precipitation supplied by fewer but more intense storms in a dryer setting (Raz Yaseef et al., 2010), allowing slow colonization of more drought-resistant plants (Koehler et al., 2005), without the dramatic reduction in vegetation cover that has been suggested to increase erosion during a few thousand years in the early Holocene (Miller et al., 2010; Hunt and Wu, 2004).

Even development of bare soil patches by itself does not cause aggradation unless high spatial connectivity occurs between patches (Mayor et al., 2008). Before this connectivity is achieved, water, sediment, and nutrients are redistributed from upslope areas and intershrub spaces to shrub areas and surface depressions with coarse cover downslope (Pierson et al., 2007; Reid et al., 1999; Mayor et al., 2008), lowering overall hillslope runoff and sediment yield (Parsons et al., 2009). Redistribution processes were probably active during the LPH in the study region because preferential winnowing of fines from the hillslopes is not represented in downslope alluvial fans of the more arid southern Mojave (McDonald et al., 2003; Harvey and Wells, 2003). Bare soil patches leaving a cover of less than 20% of shrubs would have developed only in the lower-elevation (<1000 m) areas of hot deserts, such as the northern Sonoran Desert. Modern vegetation associations, however, appear only after ca. 10 kyr B.P., suggesting a reduced cover, whereas alluvial aggradation started much earlier (Spelz et al., 2008; Armstrong et al., 2010), probably unrelated to the change in cover (Fig. 3D).

We interpret aggradation from catchments near the Gulf of California (Sierra Mayor, Fig. 3D) (Spelz et al., 2008; Armstrong et al., 2010) as indicative of regional or synoptic precipitation patterns that allow sustained overland flow during longer periods than is typical during short-duration convective storms in this low-elevation area (Kuhn and Yair, 2004; Abrahams et al., 1991). Shallower water tables in the northern Mojave at 11–10 kyr B.P. (Quade et al., 1998) that coincide with higher lake levels in southern California and northern Baja California (e.g., Negrini et al., 2006) also support enhanced synoptic-scale precipitation rather than convective rainfall, the latter commonly identified as one of the largest contributors to LPH aggradation (Bull, 1991; Reheis et al., 2005; Miller et al., 2010).

CONCLUSIONS AND IMPLICATIONS

The ambiguous relation between compositional changes in vegetation of desert catchments and the onset of regional alluvial fan aggradation indicates that broad-scale vegetation shifts had a smaller role in LPH aggradation relative to climate-driven changes in synoptic patterns and their local expression. Other factors such as changes in the frequency of storm type and intensity and local soil hydrology are probably more important in driving erosion of soils and sediments beyond a threshold, resulting in alluvial aggradation. We are clearly not advocating abandoning the commonly applied model of Bull (1991) but argue that a greater emphasis be applied to an integration of climatic, soil, and hydrologic processes affecting sediment yield and alluvial aggradation. Integrated studies linking synoptic weather patterns and activity of geomorphic processes are warranted, especially in regard to fan aggradation that occurred before the LPH. Research on specific sites with well-characterized temporal changes in vegetation and sedimentation (Harvey et al., 1999; Enzel et al., 2012), the consideration of the local expression of synoptic to mesoscale patterns (Miller et al., 2010; McDonald et al., 2003; Armstrong et al., 2010) and their evolution, along with that of other hillslope properties that affect runoff and sediment yield (Parsons et al., 2009; Kuhn and Yair, 2004; Abrahams et al., 1991; Enzel et al., 2012), will give an improved understanding of how arid region hillslope processes respond to climate change. This research would also imply reassessment of the model response of hillslopes to aridification from global climate change (Miller et al., 2010), with implications for ecosystem functions in arid regions of southwestern North America and other equally vulnerable areas of the world.

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