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Co-development of alluvial fan surfaces and arid botanical communities, Stonewall Flat, Nevada, USA

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ABSTRACT: Arid alluvial fan and fluvial dry wash surfaces in Stonewall Flat, Nevada, USA, are characterized using surface geomorphic surveys, soil pits, botanical line surveys, and varnish microlamination dating techniques. Active and abandoned washes, and active fan surfaces are dominated by primary geomorphic processes of high-energy sedimentation from flash floods. These surfaces are characterized by bar and swale topography, a lack of stone pavements, soil horizons, and rock varnish. Younger terraces and slightly older intermediate fan surfaces are in transition from primary sedimentation processes to lower energy secondary surface-modifying processes of sheet wash and eolian transport and deposition. These surfaces are characterized by faint to no bar and swale topography, incipient to moderately well-developed pavements and soil horizons, and abundant coppices. Old and stable fan surfaces are dominated by lower energy secondary processes and manifest well-developed pavements, soils, and sparse coppices around widely distributed shrubs. Varnish microlamination dating yields ages of 13·15 ka for intermediate fan surfaces and 25·55 to 86·75 ka for stable fan surfaces. Plant communities co-developing with these surfaces affect and are affected by both primary and secondary geomorphic fan processes. Relatively active surfaces contain few woody species. Co-dominance of shrubs and annuals with abundant annuals between the shrubs is characteristic of surfaces transitional from primary processes to secondary processes. Stable surfaces dominated by secondary processes are characterized by woody perennials, with long-lived woody species inhabiting the oldest surfaces. Feedback mechanisms between early botanical communities and eolian deposition affect coppice and pavement development. In turn, these surface features control both the composition and distribution of botanical communities on older, more stable surfaces. Published 2012. This article is a U.S. Government work and is in the public domain in the USA.

KEYWORDS: alluvial fan; arid botanical community; varnish microlamination dating; desert pavement; arroyo

Introduction

The concepts of co-evolution of biological communities and niche construction of earth surface landforms involving feedback mechanisms between biotic and abiotic processes has informed numerous studies in recent years. For example, continental-scale changes in co-developed land surfaces, including early soil development, and evolution within biological communities, have been proposed as coupled evolutionary processes that occurred prior to and during the early Silurian colonization of land plants (Corenblit and Steiger, 2009). Similarly, the proliferation of terrestrial plant roots from the Silurian botanical land colonization accelerated weathering, which contributed to the formation of Devonian and Mississippian marine black shales (Algeo *et al*., 1995). These and numerous similar studies suggest that plant species and geomorphic processes interact to produce co-evolving biological communities and associated landscapes (Corenblit *et al*., 2008). A number of studies have also focused on much more local biotic/abiotic interactions in geomorphic processes that occur at timescales much shorter than those involving evolutionary change. Viles *et al*. (2008) demonstrated that biotic the factors of vegetation, microbiotic soil crusts, bioturbation, and grazing affected sediment formation, transport, and deposition in several geomorphic settings disturbed by climatic and human impacts. Stoffel and Wilford (2012) reviewed the interdependencies between botanical communities and erosion, sediment transport, and deposition resulting from floods and debris flows in upland catchment basins and fans in wet environments. A study by Quade *et al*. (1995) revealed how different plant communities in arid and semi-arid valleys with springs are distributed based on the depth to groundwater, and how that distribution of plant communities affects surface sedimentation. The present study examines the change over time of similar plant/surface sedimentation dynamics in an arid fan environment.

This study was conducted on Stonewall Flat in the north-western corner of the US Air Force Nevada Test and Training Range (NTTR) located in southern Nevada, USA (Figure 1). It was initially

Figure 1. The study area is in the north-western part of the Nevada Test and Training Range (NTTR) in southern Nevada, USA.

designed to establish criteria for estimating surface stability related to the preservation of cultural features in an arid environment, in support of the Nellis Air Force Base cultural resource program. In the event, observed features and inferred interactions between geomorphic processes and biological communities were considered as sufficiently interesting to a broader audience that the Air Force supported publication of these results. We propose that initial sedimentation in arid washes and alluvial fans is dominated by punctuated, high-energy, primarily aqueous deposition that favors certain plant communities. As these arid surfaces begin to manifest a certain level of stability, eolian sedimentary processes become prominent, with feedback mechanisms between the co-developing botanical communities and the eolian redistribution of fine sediment. Arid fan surfaces with long-term stability host robust stone pavements and desert soils that further effect vegetation composition and distribution, which in turn affects bioturbation. Rock varnish microlamination (VML) dating method is employed here to determine surface exposure ages for alluvial fans of apparent intermediate and long-term stability.

Regional setting

Stonewall Flat is located in the south-western part of Nevada, USA, in the Basin and Range province. This region is characterized by internally draining basins surrounded by high mountains and an absence of through-flowing rivers. The valleys typically manifest a central dry-lake playa representing local base level surrounded by alluvial fans and bajadas constructed of sediment originating in the surrounding mountains. Stonewall Flat is a structural and hydrologic basin bounded by Stonewall Mountain (2534 m) to the south, the Cactus Range (2300 m) to the east, the Goldfield Hills (2092 m) to the north and northwest, and the Cuprite Hills (1850 m) to the west. Stonewall Flat contains two playas, a small western playa at 1434 m and a larger eastern playa at 1405 m. Stonewall Mountain is composed of Miocene welded and non-welded rhyolitic tuffs of the Stonewall volcanic center, whereas the Goldfield Hills and Cuprite Hills are composed of rhyolitic to andesitic tuffs and lavas associated with the Oligocene-Miocene Goldfield caldera complex. The Cactus Range contains rhyolite, dacite, and andesite tuffs and lavas associated with several volcanic centers within the surrounding southwest Nevada volcanic field. Hydrothermal activity associated with the regional volcanism has argillically altered some tuffs and silicified other local features in the mountains surrounding Stonewall Flat.

Active alluvial fans surround the playas in Stonewall Flat, with numerous small washes located on the fans and larger washes located in canyons in the surrounding mountains. The sediment comprising the alluvial fans and dry wash fluvial deposits of Stonewall Flat is composed primarily of gravel, cobbles, and boulders of densely welded tuff, lava, and silicified tuff, sand composed primarily of quartz, feldspar, and biotite eroded from the volcanic rocks, and of silt and clay derived from both local and distant sources (Rehies *et al.*, 1995). Stonewall Mountain hosts the shortest drainages with the steepest gradients, typically dropping about 2300 m in distances of 10 km or less. Drainages from the Cactus Range drop as much as 1900 m over distances of approximately 20 km, and drainages in the Goldfield Hills drop as much as 1300 m in distances under 20 km. Civet Cat Canyon is the longest drainage discharging into Stonewall Flat, dropping 1100 m in 25 km. Only two drainages in Stonewall Mountain manifest perennial stream flow, and these for only 100 to 200 m over nick points formed by densely welded tuff exposed locally in the bottoms of two narrow canyons. All other drainages discharging into Stonewall Flat are dry washes that flow only during and after storms with significant precipitation.

The portion of the Basin and Range province containing Stonewall Flat has an arid climate with average annual precipitation ranging from 11·2 to 16·3 cm, and annual temperatures fluctuating from average winter lows of –6·7 °C to average summer highs around 36·1 °C (Climate Charts Website, 2011). In the vicinity of Stonewall Flat annual precipitation is dominated by winter storms with a secondary contribution from summer monsoonal precipitation. Plant communities in and around the study area are characteristic of the southern Great Basin. Shrubs and sub-shrubs dominate most plant communities. Annual and perennial forbs vary in abundance throughout the study area, though annuals tend to occur with greater combined abundance than perennials, and annuals may occasionally dominate localized patches. Grasses are generally sparse, as are non-native species which occur sporadically and contribute very little to total vegetative cover. Dominant shrub and sub-shrub species in the study area include; fourwing saltbush (*Atriplex canescens*), shadscale saltbush (*Atriplex confertifolia*), Death Valley jointfir (*Ephedra funerea*), spiny hopsage (*Grayia spinosa*), burrobrush (*Hymenoclea salsola*), winterfat (*Krascheninnikovia lanata*), and bud sagebrush (*Picrothamnus desertorum*). Sand gilia (*Aliciella leptomeria*), Esteve's pincushion (*Chaenactis steviodes*), flatcrown buckwheat (*Eriogonum deflexum*), and whitestem blazingstar (*Mentzelia albicaulis*) are among the most common herbaceous species.

Recent Fan Research

In arid environments, fluvial processes dominate the surface-modifying geomorphic activities in the dry washes of canyon bottoms and alluvial fan channels. Ephemeral streams in arid regions are subjected to a wide variety of runoff events distributed unevenly in time, but the rare catastrophic flood event dominates sediment transport with high velocity/high volume flow regimes that result in exceptionally high suspended load (Baker, 1977; Powell, 2009). Desert canyons and alluvial fans are very effective in transforming precipitation and runoff into concentrated 'flashing' flows, resulting in more flood events than typically occurs in humid and temperate perennial streams of similar drainage basin size (Baker, 1977; Osterkamp and Friedman, 2000). Braided streams are more common in arid ephemeral stream settings, resulting from high velocity but variable discharge, dominant bedload transport, and erodible banks. Potentially this represents the equilibrium stream bed type for arid environments (Powell, 2009). The deposits resulting from these arid stream processes are recognized in the active washes and abandoned wash surfaces observed in the canyons surrounding Stonewall Flat.

Alluvial fan formation is dominated by flowing water-driven processes and gravity-driven processes. Primary sedimentary processes in fan development transport sediment from the upland drainage basin down-gradient to the mountain front where fan-shaped deposits form. The primary sedimentary processes include rockfall, rock slides, rock avalanches, incised channel floods, and sheet floods. These processes are triggered primarily by intense precipitation events, although various rockfalls, rock slides, and rock avalanches can also be triggered by earthquakes. In any event, each process represents an infrequent, high energy, short duration event that results in the transport and deposition of coarse, poorly sorted detritus potentially ranging in size from blocks to sand (Blair and McPherson, 1994). Individual fans are often dominated be a specific primary process that is particularly well suited to the gradient/climate/upland basin geology of that fan (Blair and McPherson, 2009; Blair, 1999a, 1999b, 1999c, 1999d). Secondary processes modify the fan deposits formed by the primary processes, and include overland sheet flow, eolian erosion and deposition, bioturbation, soil development, and weathering. Secondary processes typically are lower energy events that occur more frequently and tend to dominate fan surface processes except where primary processes are focused, such as in active channels (Blair, 1987).

The primary process of incised channel flooding remains confined to active washes on alluvial fans and in canyon bottoms. During rising flow bed erosion occurs, and peak flow accommodates both erosion and sediment transport. During falling flow deposition occurs, with increasingly finer sediment deposited with decreasing flow (Blair, 1987, 1999a, 2000). Drapes of finer sediment are deposited as overbank deposits during falling flow from channel floods that broach their banks. Lateral repositioning of incised channels accompanied by channel incision results in new active channels and the development of abandoned channel surfaces and terraces (Blair, 1999b).

Sheet floods are short term, high energy, high flow events where an incised channel flood reaches the distal portion of the fan without appreciable loss of velocity or volume, and becomes unconfined as it broaches the lower banks of the channel. This can also occur farther up the fan due to a sudden increase in runoff volume. Large sheet floods are catastrophic events that deposit tremendous volumes of sediment as distinct horizontal bedded couplets of alternating coarse, imbricated, clast-supported sediment and finer, laminated sediment (Blair, 1987, 2000). The upper surface of sheet flood deposits typically manifest cobbly and gravelly patches surrounded by finer sandy deposits; these beds result from temporary critical flow regimes that form, migrate, then dissipate (Blair and McPherson, 1994; Blair, 1987). This type of bedding has been observed in soil pits on alluvial fans in basins adjacent to Stonewall Flat (Dickerson, 2006, 2009).

Sheet flow is the most common secondary process modifying alluvial fan surfaces, and occurs more frequently than the primary constructive processes discussed earlier. Sheet flow can winnow silt and sand out of surface deposits, leaving a lag of coarser gravel on the surface. Silt and sand are thus transported towards the distal margins of the fan (Blair and McPherson, 2009). Eolian erosion can winnow out the finest fraction of surface sediment from some locations (Al-Farraj and Harvey, 2000), and can deposit sheet sands, sand ramps, dunes, and coppice deposits at other locations (Blair and McPherson, 1992). Bioturbation via plant roots, burrowing insects, and burrowing animals disrupt primary bedding and homogenize surface sediment. Plants also host small coppice deposits and attract small burrowing animals that act to mix sediment to a greater extent than the plant roots can accomplished alone (Blair and McPherson, 2009).

Quade *et al*. (1995) observed a dynamic relation between near-surface groundwater, desert plants, and surface sedimentation in arid valleys. Valleys with spring discharge exhibit a change from xerophyte plant communities to phreatophyte plant communities where the groundwater table approaches to within approximately 6 m of the surface. The space between plants in the xerophyte communities allows surface runoff to transport and deposit sediment up to cobble size, whereas the more densely packed phreatophytes filter out the gravel and cobbles from surface runoff and allow only sand and silt to be transported and deposited. The dense grass and wet soils at the spring discharge sites trap windblown silt and dust, creating very fine grain surface deposits that can contain dark, organic mats. As climatic conditions change, these zones can expand, contract, and migrate within the valley as a function of changing near-surface groundwater conditions and shifting discharge sites.

Methods

Field observations

Detailed field observations were made of the surface morphology and sedimentary features of fluvial dry wash and alluvial fan surfaces, including. sediment type (clast size, sorting, rounding, and induration), bedform type (bars, channels, coppices, overbank deposits, relict sedimentary features, pavements), spatial distribution of deposits relative to relict features and vegetation cover, biogenic features (bioturbation, microbiotic soil crusts), and secondary mineral coatings (pedogenic carbonate coatings, iron oxide staining, rock varnish) for each site. The initial field visits involved reconnaissance of all potential surfaces within the dry wash and alluvial fan depositional environments, followed by detailed data collection. Field stations on fluvial and alluvial surfaces were visited in order of apparent increasing age and stability, with dry wash data collected prior to alluvial fan data. Shallow soil pits were dug on selected active, transitional, and stable alluvial fan surfaces to record progressive development of soil horizons. Several traverses from the proximal edge of a fan near the mountain front to the distal edge of the fan on the margins of the playa were completed in order to record systematic changes in surface sediment content, Av horizon development, and surface morphology. Surface changes were noted on alluvial fans from axial fan washes to relatively active fan surfaces, transitional fan surfaces, and stable fan surfaces. In the dry wash fluvial environment shallow soil pits were dug on active wash surfaces, abandoned wash surfaces, a younger terrace surface, and an older terrace surface. Many of the observations made in these environments benefited from fortuitously timed field visits during or immediately following large storms in this arid environment.

VML dating

Rock varnish is a slowly accreting manganese (Mn)- and iron (Fe)-rich dark coating on subaerially exposed rock surfaces in arid to semi-arid deserts (Dorn and Oberlander, 1982; Liu *et al*., 2000). Because of its sedimentary origin, varnish often exhibits a layered microstratigraphy in ultra-thin sections under microscopic examination with transmitted polarized light (Liu and Dorn, 1996). In the Great Basin of the western USA, Mn-poor yellow layers in varnish were formed during the dry Holocene (Liu and Dorn, 1996). The Mn-rich black layers were deposited during the last glacial when the Great Basin was much wetter than at present (Liu *et al*., 2000; Broecker and Liu, 2001). The Mn-intermediate orange layers were deposited when the climate was intermediate between maximum wet and maximum dry periods (Liu and Dorn, 1996; Broecker and Liu, 2001). The microlamination patterns observed in varnish microstratigraphy thus reflect past climate changes (Liu and Dorn, 1996; Liu *et al*., 2000; Broecker and Liu, 2001).

VML dating is a climatic correlation-based age determination technique (Liu, 2003; Liu and Broecker, 2007, 2008a). The basic assumption behind this dating approach is that VML patterns are produced by climatic changes. Because the climatic signals recorded in varnish are regionally contemporaneous (Liu and Dorn, 1996; Liu *et al*., 2000), VML can be used as a dating tool to provide minimum-limiting surface exposure ages for geomorphic surfaces in deserts once radiometrically calibrated and climatically correlated. The reliability of VML dating was confirmed by a blind test comparing VML dates with cosmogenic chlorine-36 (^{36}Cl) dates derived independently from the same previously undated lava surfaces in the Mojave Desert (Liu, 2003; Marston, 2003; Phillips, 2003). Early studies (Liu and Dorn, 1996; Liu, 2003) indicated that VML dating has the potential to yield surface exposure ages with an accuracy of approximately 10^3–10^4 years for late Pleistocene landforms, based on a temporal correlation of the varnish wetness record with sudden sub-Milankovitch timescale changes such as Younger Dryas and Hienrich events in the North Atlantic region. Recent studies (Liu and Broecker, 2007, 2008b) show that the microstratigraphy of fine-grained and fast-accreting varnish records millennial-scale wet events correlate in time with Holocene and late Pleistocene millennia-scale cooling events in the North Atlantic and Greenland (Meese *et al*., 1994; Bond *et al*., 1999). Such millennial-scale varnish microstratigraphy makes it possible to VML date geomorphic features with improved accuracy of approximately 10^2–10^3 years (Figure 2).

In this study, apparent alluvial fan surface ages based on surface morphology were corroborated using VML dating method. Surface rock varnish samples were collected from boulders located on older transitional and stable fan surfaces. Sampling was done to avoid rock surfaces with post-depositional leaching or abrasion of the varnish, or spallation that removes older varnished surfaces (Liu and Broecker, 2008a; Dorn, 2009). Several dozen boulders were examined at each sample site for the presence of suitable 1–3 mm-sized varnish-filled 'microbasins' on the top of the boulder and for the absence of spallation surfaces. Multiple thin sections of rock varnish microbasins were made from each sample to increase the odds of uncovering the most complete and unambiguous microstratigraphic record. Selected thin sections were then photographed under a light microscope using transmitted polarized light, yielding high resolution (×500) color images of varnish microstratigraphies for layering pattern analysis and VML age estimates (Liu, 2003; Liu and Broecker, 2007, 2008a, 2008b). VML age estimations for transitional and stable alluvial fan surfaces were compared to beryllium-10 (^{10}Be) cosmogenic surface age determinations for similar looking surfaces on adjacent fans in Stonewall Flat (Dickerson and Bierman, In press). Both dating techniques yielded similar results for fan surfaces manifesting similar surface morphologies.

Botanical survey and analysis

The botanical component of this study was conducted in Stonewall Flat. Ten plots were sampled in mid-June of 2010 for vegetative cover by species around the Stonewall Flat playa and in Civet Cat Canyon southeast of the playa. Four sample plots were located on surfaces associated with fluvial dry wash surfaces and six plots were located on alluvial fan surfaces. Plots were systematically located so as to capture a range of apparent surface ages in both fluvial and alluvial systems. Relative ages of the surfaces sampled in both fluvial and alluvial systems were estimated based on geomorphological characteristics and ranged from active washes to stable alluvial fans. Each plot comprised one 50 m transect line. Transect lines were oriented so as to capture the range of variability across the plant community on a given geomorphological surface, to sample the plant community most representative of that surface, and to ensure the plot was located entirely within the margins of that surface. Plant cover was estimated using line interception techniques (Elzinga *et al*., 1998) and plant nomenclature was assigned according to the PLANTS database (USDA, NRCS, 2010).

The floristic composition of the 10 plots sampled across various fluvial and alluvial surfaces was compared using multivariate analyses and functional group summaries. Fluvial and alluvial plots were pooled and ranked according to apparent age and stability. Multivariate analyses on plots ranked by age and stability included pair-wise comparisons of all potential plot combinations using a similarity index matrix and a polar plot ordination. We used the complement of the Bray–Curtis measure of dissimilarity as our similarity metric (Krebs, 1999). The Bray–Curtis metric calculates similarity by comparing absolute cover values on a species by species basis for comparisons between each pair of plots and returns a proportional value between zero and one. A value of zero indicates that the two plots have no species in common and a value of one indicates that the two plots are identical, containing the same species at the same absolute cover values for each species. The Bray–Curtis measure is particularly sensitive to fluctuations in absolute cover values which results in low expected maximum similarity values (Krebs, 1999). For example, two plots having similar species compositions with similar relative cover values may receive a low similarity score if total vegetation cover between the two plots varies in response to local stochastic factors. Consequently, the range of similarity values represented for all pair-wise combinations will often be concentrated toward the middle- to lower-end of the zero to one similarity scale, even when several pair-wise combinations of plots are similar in terms of proportional species composition. Thus, Bray–Curtis similarity values can be useful for identifying which plots are most or least similar to one another, but moderate values do not necessarily indicate substantial differences in relative species cover and composition.

Polar plot ordinations were used for comparison among the 10 sample plots. Interpreting information about the distribution of plant communities on the landscape is greatly facilitated by using polar plot ordinations to visualize similarity/dissimilarity relationships (McCune and Grace, 2002). Ordinations allow investigators to rescale similarity/dissimilarity scores and view plot relations in three-dimensional space. For example, plots from landscapes in which plant communities exhibited gradual spatial and/or temporal variation generally result in ordination plots manifesting well-spaced sub-linear to linear patterns. Plant communities that tend to exhibit discrete and/or abrupt pattern changes plot in clusters in three-dimensional ordination space. To better understand the plot spacing patterns resulting from the polar plot ordination, we summarized species cover by plot into functional group cover by plot. Functional groups were based

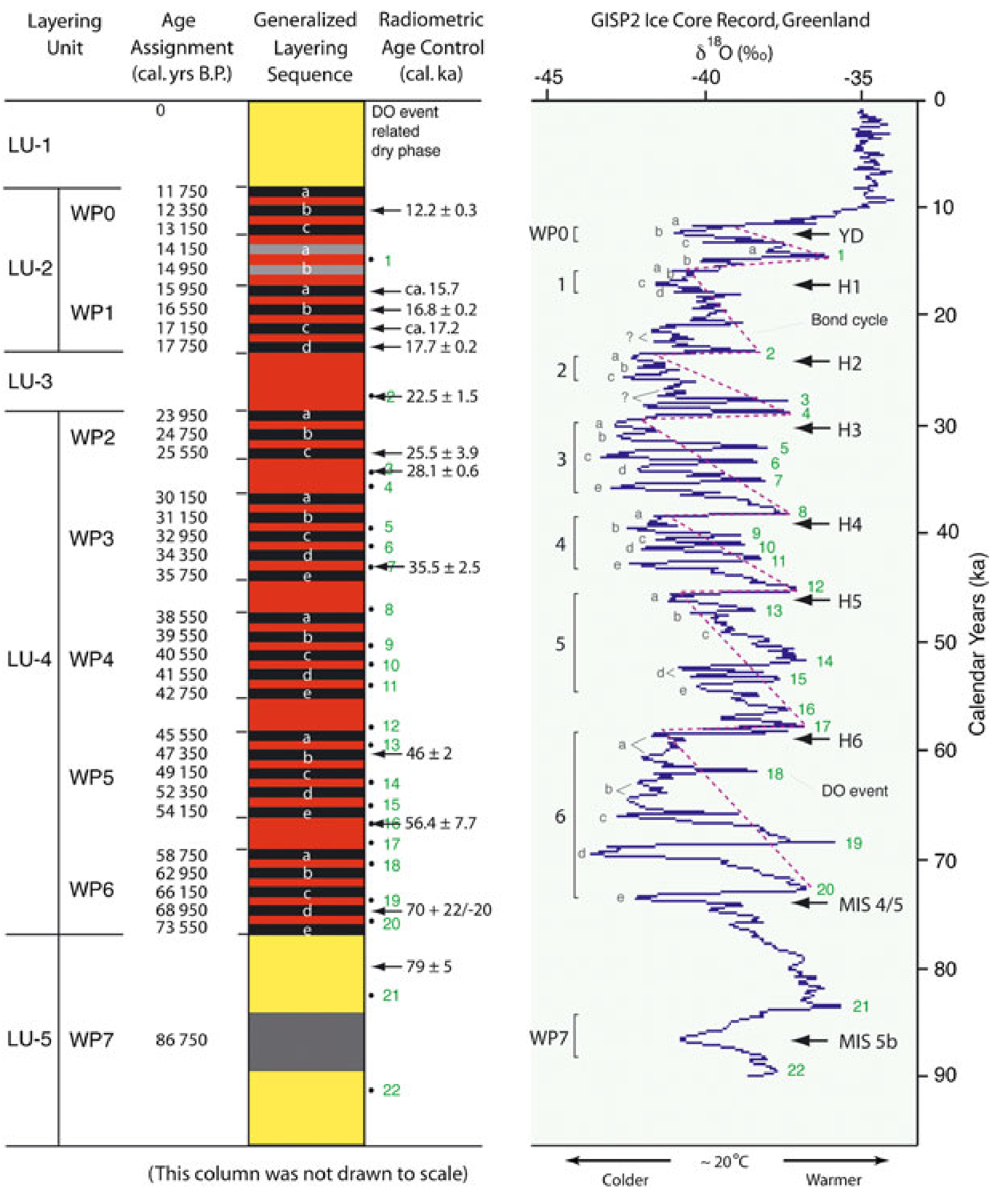

Figure 2. Radiometric age calibration (Liu *et al.*, 2000; Liu, 2003) and temporal correlation of the generalized late Pleistocene and Holocene varnish climate record and microstratigraphy for the western US deserts. Age constraints are reported in cal yr BP (± 1 sigma if applicable). Age assignments are based on a presumable correlation between varnish and GISP2 ice core records for the latest Pleistocene (Grootes *et al.*, 1993; Meese *et al.*, 1994; Bond *et al.*, 1999) and between varnish and deep sea sediment records for Holocene (Liu and Broecker, 2007). Evidence from Liu (2003) and Liu and Broecker (2007, 2008a) indicates that wet paleoclimate periods represented by dark layers in the varnish record most likely correlate with cold periods represented by oxygen isotopic troughs in the GISP2 ice-core record. Age assignments for dark layers WP0 through WP6 are from Liu (2003), with the age assignments for the millennial-scale dark bands in LU-2 and LU-4 being based primarily on climatic correlation of the varnish record with the GISP2 ice core record (Grootes *et al.*, 1993; Meese *et al.*, 1994). LU, Layering Unit; WH, Wet Event in Holocene; WP, Wet Event in Pleistocene; H, Heinrich Event; H0, Younger Dryas; OD, Older Dryas; IACP, Intra-Allerod Cold Period (Liu and Broecker, 2008b).

on the nativity, growth form, and duration of species. Non-native species were excluded from these analyses because they contributed very little to total cover and because they may respond to abiotic factors, such as surface age and stability, differently from native species. Both absolute and relative cover of annual and perennial native species was considered in these analyses, where relative cover is the percent cover of each species normalized to total vegetation cover for all species in the plot.

Results

Geomorphic characteristics of fluvial dry wash surfaces

The active washes in the canyons and on the fans of Stonewall Flat are dominated by braided streambeds composed of fair to poorly sorted, unconsolidated sediment forming gravel channels and cobble bars. Sand is often concentrated along the edges of active channels and behind the sparse bushes growing within the channels. There is no soil developed, no stone pavements or Av horizons, no rock varnish, and no microbiotic soil crusts on these active wash surfaces. Soil pits excavated into these surfaces revealed unconsolidated, poorly sorted, fine to coarse sand and gravel, with no cementation or induration, no caliche or mineral oxide coatings on any clasts, and no bioturbation. Recently abandoned wash surfaces are composed of fair to poorly sorted sand, gravel, and cobbles, with some boulders. These surfaces typically lie 10 to 15 cm above active wash surfaces, and exhibit a bar and swale topography partially covered by overbank flood deposits of silt and fine sand. Some silt and sand is deposited on the lee side of desert shrubs. These sediments occasionally host juvenile microbiotic soil crusts as well as some small animal burrows. Very thin coatings of pedogenic carbonate occasionally occur on the undersides of half-buried cobbles and boulders, but there is no pavement or Av horizon, and no rock varnish.

Older abandoned wash surfaces are composed of poorly sorted silt, sand, gravel, cobbles, and some boulders. These surfaces preserve relict bar and swale topography that overbank and eolian sedimentation has begun to obscure. Bioturbation by burrowing animals is common. Microbiotic soil crusts typically are well developed on silty and sandy surfaces, but absent from gravelly surfaces. Carbonate coatings on half-buried boulders and cobbles are common, but rock varnish is absent. Locally, incipient pavements with subjacent cumulate layers dominated by silt, clay, and fine sand have started to develop. A soil pit excavated into one of these surfaces revealed a loose layer of gravel on the surface but no Av horizon *per se*. Beneath the surface layer of loose gravel lay 10 cm of poorly sorted and unconsolidated, fine to coarse sand with minor clay, silt, and sub-angular to sub-rounded gravel that exhibited no horizontal bedding. Below this was another 15 cm of unconsolidated, poorly sorted, fine to coarse sand and matrix-supported, sub-angular to sub-rounded gravel to 3 cm, with no cementation and no carbonate or iron oxide coatings on the clasts.

Terrace surfaces of different ages exist from one to several meters above the various abandoned wash surfaces. These surfaces are quite flat and exhibit no remnants of bar and swale topography. They are dominated by intermediate to mature pavements underlain by incipient to well-developed Av horizons. Rock varnish is common but microbiotic soil crusts are rare. Fine surface sediment is confined to coppice deposits around shrubs. Locally, large burrow mounds of silt and fine sand exist around the large living or dead desert shrubs. These burrow mounds correlate to the first two stages of development for plant scar mounds discussed by McAuliffe and McDonald (2006, figures 6A and 6B). Pedogenic carbonate coatings on the underside of half-buried cobbles and boulders are rare to common, and iron oxide coatings are very common. A soil pit dug into a younger terrace surface showed a 6 mm thick Av horizon composed of silt, sand, and clay, with some vesicles, a subjacent 3 cm thick, weakly consolidated and friable A horizon composed of silt, sand, and clay with some small horizontal open partings, but no carbonate or oxide coatings, and a very weakly consolidated, 7·5 cm thick, lower A horizon composed of fine to coarse sand, minor silt and clay, with weak horizontal bedded. Below this lay 14 cm of poorly sorted and very weakly consolidated sand and gravel with no bedded and no carbonate coatings or oxide staining. A soil pit dug into a higher and presumable older terrace surface in the same canyon contained a 8 cm thick, yellowish-gray, extremely vesicular Av horizon composed of moderately well consolidated clay, silt, and very minor very fine sand. Below this was a 8 cm thick, reddish-gray upper B horizon composed of very well consolidated clay and silt with minor small roots but no horizontal bedded, and a 12 cm thick, dark yellowish-gray lower B horizon composed of poorly consolidated sand, with some clay and gravel, but without horizontal bedded or carbonate coatings or oxide staining on any of the clasts. The principle attributes defining the dry wash channel and terrace surfaces are tabulated in Table I. The qualitative age estimates for surface stability of recent and older wash surfaces are supported by the age of undisturbed cultural sites associated with these surfaces in portions of the NTTR (Cook *et al.*, 2009).

Geomorphic characteristics of alluvial fan surfaces

Relatively active alluvial fan surfaces display features similar to those observed on active wash, recently abandoned wash, and older abandoned wash surfaces in the canyons surrounding Stonewall Flat. The surface sediments are composed of unconsolidated, poorly sorted, fine to coarse sand and gravel, with some silt, cobbles, and boulders. The sediment on relatively active fan surfaces is generally finer than the surface sediment on adjacent more stable fan surfaces, although coarseness and rounding is strongly dependant on location on the fan relative to its proximal and distal margins. These fan surfaces typically exhibit a bar and swale topography slightly covered by sand and silt. Eolian deposits exist as coppice deposits around desert shrubs. Bioturbation by burrowing animals is common. Soil pits excavated into the upper meter of relatively active fan surfaces revealed a lack of near-surface horizon development. Microbiotic soil crusts exist locally on the sandier portions of these surfaces, and subtle shrinkage cracks are common on the distal portions of the fan. Pedogenic carbonate was often observed coating half of a cobble or boulder, but the random orientation of these clasts indicates that most of them had been transported from farther up the fan where the coatings had formed. Desert pavement and rock varnish are absent.

Intermediate alluvial fan surfaces in transition from being dominated by primary fan processes to being dominated by secondary processes occupy a broad middle ground between the relatively active fan surfaces and the stable fan surfaces. These surfaces often appear similar to the terrace surfaces observed in the canyons surrounding Stonewall Flat. Intermediate alluvial fan surfaces in Stonewall Flat typically lie more than 30 cm above adjacent dry wash channels on the alluvial fans. In general, the

Table I. Dry wash channel and terrace surface attributes.

	< Youngest			Oldest >
Surface	Active wash	Abandoned wash	Young terrace	Old terrace
Assumed stability	Years	Years – decades	Centuries	Millenia
Fluvial sediments	Dominant on surface	Present on surface	Obscure on surface	Present at depth[a]
Overbank sediments	None	Common	Trace	None
Eolian sediments	None	Trace	Common (coppice deposits)	Common (coppice deposits)
Av horizon	None	None	Incipient – moderate	Well developed
Carbonate Coating clasts	None	Trace	Minor – well developed	Minor – well developed
Microbiotic soil crusts[b]	None	Trace – minor	Minor – well developed	Very rare
Desert pavement	None	None	Weakly – moderately developed	Well developed
Rock varnish	None	None	None	Common
Vegetation	Minor annuals, Minor shrubs	Annuals + minor shrubs	Annuals + shrubs	Shrubs + minor annuals

[a]Older fluvial sediments buried beneath the soil and pavement.

[b]Also known as cryptogam, cryptogammic soil, and microbial crusts, composed of fungus and cyanobacteria on sandy soil.

surfaces of intermediate fan surfaces contain more gravel than adjacent active fan surfaces, and more sand than adjacent stable fan surfaces. Cleanly fractured boulders and cobbles occur on some of these surfaces. In the absence of any evidence for mechanical stress being imparted onto these fractured boulders, (such as chip marks on the boulders, or vehicle tracks or inert ordnance near them) we infer that these fractures resulted from thermal stress as discussed in McFadden *et al.* (2005). Younger-appearing intermediate fan surfaces often exhibit vestiges of the bar and swale morphology, whereas older-appearing intermediate surfaces are more planar. Surficial gravel deposits range from proto-pavements overlying an incipient cumulate layer of silt and sand, to intermediate pavements with weakly to moderately well-developed Av horizons. Where the surface gravel is more sparsely distributed near the distal edge of the fan close to the valley center, diffuse shrinkage cracks exist. Coppice deposits of silt and fine sand are common around desert shrubs of all sizes. Locally, coppice deposits are heavily burrowed. Microbiotic soil crusts are rare and favor the sandier portions of the fan surface. On the intermediate fan surfaces of Stonewall Flat, pedogenic carbonate coatings on half-buried cobbles and boulders occur far less often than does iron oxide staining, which is fairly common. Rock varnish ranges from poorly developed to fairly well developed on boulders and some of the larger cobbles.

Stable alluvial fan surfaces are surfaces that have been dominated by secondary processes for thousands of years and are among the oldest non-bedrock surfaces in the southern Great Basin of the United States (Valentine and Harrington, 2006). These fan surfaces have many features in common with the oldest terrace surfaces in the canyons surrounding Stonewall Flat, and can lie anywhere from several decimeters to several meters above surrounding, less stable fan surfaces. Gravel, with subordinate amounts of cobbles and boulders dominate stable fan surfaces and form extensive, well-developed stone pavements. These pavements typically are stained with rock varnish. As a general observation, the larger cobbles and boulders manifest more pervasive coatings of rock varnish than the smaller gravel clasts. The oldest-appearing of these pavements contain clasts that are cracked but otherwise undisturbed, possibly due to diurnal thermal stress (McFadden *et al.*, 2005; Adelsberger and Smith, 2008). Av horizons greater than 8 cm thick and composed of clay and silt have developed beneath the pavements, with clay content increasing with age (McFadden *et al.*, 1998; Anderson *et al.*, 2002). Surface deposits of silt and sand are found only in coppice deposits around the larger desert shrubs. These coppice deposits often host animal burrows and herbaceous annuals, although many coppice deposits remain undisturbed by bioturbation. As on the older terrace surfaces, the bioturbated coppice deposits on stable fan surfaces resemble the two early stages of plant scar mounds of McAuliffe and McDonald (2006), although the stages represented on their figures 6C and 6D were not recognized in Stonewall Flat. Stable alluvial fan surfaces locally contain widely separated large animal burrows from mid-size animals that can easily dig through the desert pavement.

Stable fan surfaces with clay-dominated Av horizons thicker than 10 cm manifest patterned ground in the gravel clasts composing the pavement (Figure 3), here called ‘patterned pavement’. Similar types of patterned ground involving pavements and other stony desert surfaces have been observed in other deserts around the world, and are often referred to as ‘stony gilgai’. Most stony gilgai described in these deserts are tens of centimeters to several meters in diameter (Dixon, 2009), whereas the clay-rich polygons of the patterned pavements observed in Stonewall Flat are a few centimeters in diameter. Virtually all of the stony gilgai described in other deserts involve stony surfaces underlain by a clay-rich substrate with a high swelling potential located in arid climates where there is a pronounced seasonality to the annual precipitation. Although several mechanisms of formation have been proposed, they all involve some combination of vertical and horizontal stresses imparted by swelling clays (Dixon, 2009). We infer that the same shrinking and swelling behavior of the clay in the Av horizon that forms shrinkage polygons beneath the larger rocks on stable fan surfaces is also responsible for forming the patterned pavements observed in Stonewall Flat. It is possible that these patches of patterned pavement are in some way related to plant scar depressions in an advanced stage of development (McAuliffe and McDonald, 2006), although we collected insufficient data to evaluate this potentiality.

Microbiotic soil crusts typically are absent from most stable alluvial fan surfaces, even though they are observed on some older terrace deposits. Coatings of pedogenic carbonate on the undersides of partially buried cobbles and boulders can exist locally on intermediate and stable fan surfaces, but the undersides of these half-buried rocks more often are coated with a reddish iron oxide stain. The most stable fan surfaces also contain the best-developed stone pavements with interlocking gravel clasts heavily stained by varnish overlying a thick, clay-dominated Av horizon, with scattered patches of patterned

Figure 3. Patterned pavement can be found on mature alluvial fans, but is seldom observed on intermediate alluvial fans. These features require adequate time for the growth of a thick Av horizon and subsequent modification by repeated shrinking and swelling episodes driving by countless rain storms.

pavement. These types of pavements typically take many thousands of years to attain full development (Anderson *et al.*, 2002; Liu, 2003; Valentine and Harrington, 2006). The principle surface attributes of alluvial fans discussed here are shown in Table II.

Systematic changes in alluvial fan surfaces

The results of a traverse of an alluvial fan from its proximal edge near the mouth of a major wash in the Gold Field Hills to the distal edge near the valley center illustrates both the expected changes in surface sediment size and rounding, as well as the development of surface features with increasing fan stability. The upper margins of this fan are bordered by an active wash on one side and an older abandoned wash on the other side. The uppermost field station was located on a relatively active fan surface a few meters from the active wash, with subsequent field stations placed approximately 100 m apart down the fan towards the valley center. The fan surface is undisturbed by human activity until approximately 700 m down the fan where two dirt roads, an abandoned railroad grade, and an early twentieth century building disrupt the surface. The upper 700 m of the fan manifests the characteristics of a stable fan surface, whereas relatively active fan surface features predominate below the roads because of renewed sedimentation caused by the surface disturbance. The upper two field stations mark a transition from a relatively active fan surface to an intermediate fan surface; by the third field station the surface has become fairly stable by the criteria established in this study. Sediment clast size diminishes, and clast rounding increases, down the fan (Table III), results entirely consistent with previous studies (Phillips and McMahon, 1978; Graf, 1988; Parker, 1991, 1995). However, our site sample size is small and the interested reader is referred to Parker (1995) for a much more statistically robust treatment of this phenomena.

Relict bar and swale topography is noted on the relatively active fan surface, with very faint bar and swale topography observed on the intermediate fan surface. Similarly, the desert pavement goes from incipient development with a weak A soil horizon to a moderately well-developed pavement with 7–8 cm of silty Av horizon. Rock varnish exists on only the largest boulders on the relatively active fan surface but is better established on boulders and cobbles on the intermediate fan surface. Coppice deposits are more numerous on both the relatively active and intermediate fan surfaces where the surface sediments contain a higher proportion of sand than they do on the stable fan surfaces covered with stone pavements. From the third field station down to the roads, the fan surface is stable, with a well-developed pavement, a clay-dominated Av horizon, and pervasive rock varnish on boulders, cobbles, and gravel clasts alike. The central and lower portions of the fan exhibit a very stable surface with pervasive rock varnish on the pavement, up to 12 cm of well-developed Av soil horizon above a sandier A horizon, and locally developed patterned pavement. Pedogenic carbonate coatings on half-buried cobbles and boulders are fairly rare but red iron oxide staining on the lower surfaces is common. Bioturbation from burrowing animals is best developed on the relatively active surface where the surface soil is sandier and lacks pavement.

The portion of the fan below the two dirt roads manifests the surface features associated with relatively active fan surfaces. Sand and clay content in the surface sediments increases down the slope, and gravel clasts diminish in size and increase in rounding. The increasing clay content results in an increased number of shrinkage cracks towards the valley center. Bar and swale topography is more common, pavements with Av horizons are absent, and rock varnish exists only on a few large boulders nearest the roads. With the increased sand content in the surface sediment coppice deposits are more common, as are animal burrows. Pedogenic carbonate coatings formed around half-buried cobbles are somewhat more common, whereas iron oxide staining is less common. Parker (1995) noted similar physical changes in older, more stable fan surfaces that had been rejuvenated by more active fan processes. Observations from the lower part of the fan are tabulated in Table IV.

Ages of alluvial fan surfaces

VML age estimates are established for five fan surfaces in Stonewall Flat. Figure 2 shows the radiometric calibration for the generalized late Pleistocene millennial-scale varnish microstratigraphy for the western US deserts and its correlation with the $\delta^{18}O$ record in the GISP2 Greenland ice core (Liu and Broecker, 2008a). The climate correlation-based age assignments for the millennial-scale VMLs shown in Figure 3 provide the most accurate age scale upon which the VML age determinations of the fans surfaces in Stonewall Flat are made.

Sample site 2010 STF-5 is located on a fan surface characterized by more stable intermediate fan surface features. This fan surface

Table II. Alluvial fan surface attributes.

	< Youngest		Oldest >
Fan Surface	Relatively active surface	Intermediate (transitional) surface	Stable surface
Stability	Decades to centuries	Multiple millenia	Ten's of millenia
Fluvial sediments	Common on surface	Very rare on surface	None on surface Only at depth
Overbank sediments	Present	None	None
Eolian sediments	Minor	Common as coppice deposits	Common as small coppice deposits
Av horizon	None	Minor – well developed	Well developed
Pedogenic carbonate[a]	Common	Surface clasts – minor Soil clasts – minor	Surface clasts – minor Soil clasts – common
Iron staining	None	Common	Common
Cryptobiotic soil	Minor	Minor	None
Desert pavement	None	Incipient – moderately well developed	Well developed
Rock varnish	None	Minor – major	Major
Vegetation	Annuals dominant	Shrubs dominant	Shrubs dominant

[a]Carbonate coatings on half-buried surface clasts are not a common feature in Stonewall Flat, but coatings on gravel clasts in B soil horizon are more common. In Stonewall Flat iron oxide staining on half-buried clasts is far more common.

Table III. Proximal to medial alluvial fan surface characteristics.

	Proximal						Medial
	STF-7	STF-8	STF-9	STF-10	STF-11	STF-12	STF-13
Surface stability	Active-intermediate	Intermediate	Stable	Stable	Stable	Stable	Stable
Surface sediments[a]	Gravel sand cobbles boulders	Gravel cobbles minor boulders	Gravel cobbles minor boulders	Gravel cobbles minor boulders	Gravel cobbles	Gravel cobbles very minor boulders	Gravel cobbles very minor boulders
Rounding	Angular	Angular–sub-angular	Angular–sub-angular minor sub-rounded	Sub-angular sub-rounded minor angular	Sub-angular sub-rounded minor angular	Sub-angular sub-rounded minor angular	Sub-angular sub-rounded minor angular
Largest clast[b]	$65 \times 53 \times 33$ cm^3	$45 \times 35 \times 18$ cm^3	$45 \times 28 \times 8$ cm^3	$30 \times 30 \times 26$ cm^3	$28 \times 13 \times 8$ cm^3	$35 \times 23 \times 5$ cm^3	$30 \times 15 \times 13$ cm^3
Varnish[c]	Boulders	Boulders cobbles	Boulders cobbles gravel	Boulders cobbles gravel	Boulders cobbles gravel	Boulders cobbles gravel	Boulders cobbles gravel
Pavement	Incipient	Weak – moderate	Well developed	Very mature[d]	Moderate & mature	Well developed	Well developed
Coppice	Some	Minor	Some	Sparse	Some	Minor	Minor
Burrowing	Common	Minor	Some	Minor	Minor	Sparse	Sparse
Pedogenic carbonate[e]	Common	Trace	Trace	None	Trace	None	None
Fe stain[f]	Common	—	Some	Common	Common	Common	Common
Bar & swale	Relict	Very feint relict	None	None	None	None	None

[a]Clasts listed in decreasing order of abundance.
[b]Largest clast within 3 m of field station location.
[c]Clasts typically covered with rock varnish.
[d]Locally exhibited patterned pavement.
[e]Caliche coating the undersides of partially buried cobbles and boulders.
[f]As iron oxide surface stain on the buried half of cobbles and boulders.

Table IV. Medial to distal alluvial fan surface characteristics.

	Medial			Distal
	STF-14	STF-15	STF-16	STF-17
Surface stability	Active	Active	Active	Active
Surface sediments[a]	Sand gravel	Sand fine gravel	Sand & clay gravel	Sand & clay gravel
Rounding	Sub-angular–sub-rounded	Sub-angular–sub-rounded	Sub-rounded–sub-angular	Sub-rounded–sub-angular
Largest clast[b]	$20 \times 13 \times 3$ cm^3	$13 \times 10 \times 5$ cm^3	$23 \times 13 \times 13$ cm^3	$10 \times 8 \times 5$ cm^3
Varnish[c]	Boulders	None	None	None
Pavement	None	None	None	None
Coppice	Common	Common	Common	Common
Burrowing	Common	Some	Some	Some
Pedogenic carbonate[d]	Trace	Trace	Trace	Some
Fe Stain[e]	Common	None	None	None
Bar & swale	Common	—	None	Some

[a]Clasts listed in decreasing order of abundance.
[b]Largest clast within 3 m of field station location.
[c]Clasts typically covered with rock varnish.
[d]Caliche coating the undersides of partially buried cobbles and boulders.
[e]As iron oxide surface stain on the buried half of cobbles and boulders.

hosts relict bar and swale topography and manifests a fairly well-developed pavement. Rock varnish exists on boulders and cobbles only, coppice deposits are common and varied, and bioturbation from burrowing animals is common. This fan surface is also more densely vegetated than the more stable fan surfaces at the other VML sample sites. The soil at this site contains a 5 cm thick, medium yellowish-gray, very vesicular upper Av horizon composed of clay, silt, and very minor sand, and a 3 cm thick, slightly redder, lower Av horizon composed of clay, silt, and very minor sand with much smaller and fewer vesicles and small open horizontal partings near the bottom. The combined Av horizons are fairly well consolidated, with the degree of consolidation increasing downward. The B horizon is 13 cm thick, reddish gray to grayish red, and composed of poorly sorted and very weakly consolidated silt, clay, and fine gravel, with no bedding or vertical features. Some of the larger gravel clasts within the B horizon have carbonate coatings and iron oxide stains. Below this B horizon there is 6 cm of weakly consolidated, light reddish-gray gravel, sand, silt, and clay with no horizontal bedding and no carbonate coatings. The oldest microlamination patterns observed in ultra-thin sections from sample location 2010 STF-5 are LU-1/LU-2 (WP0c), with an estimated age of 13·15 ka.

Sample site 2010 STF-6 is located near the center of the stable alluvial fan described in the detailed proximal-to-distal surface traverse. Here the fan surface is flat with no relict bar and swale topography, and has a well-developed pavement with interlocking surface clasts, and a well-developed Av horizon. Rock varnish is pervasive, covering boulders, cobbles, and gravel clasts. Locally, patterned pavement has developed, fractured boulders similar in appearance to those described in McFadden *et al*. (2005) are common, and coppice deposits are sparse and restricted to the larger shrubs. Burrowing is sparse and restricted to large animals capable of digging through the surface pavement. The soil at this site contains a 6 cm thick, light to medium yellowish-gray, very vesicular upper Av horizon composed of clay, silt, and some fine to coarse sand, and a 3 cm thick, reddish gray, lower Av horizon composed of clay, silt, and some fine to coarse sand, with smaller vesicles and small open horizontal partings near the bottom. The combined Av horizon is moderately consolidated with the degree of consolidation increasing downward. The upper part of the B horizon is 7 cm thick, reddish gray to grayish red, and composed of very weakly consolidated silt, clay, and minor sand with no bedding. The lower B horizon is 5 cm thick and composed of poorly sorted, matrix-supported, weakly indurate gravel, sand, silt, and clay, with carbonate coatings and iron oxide staining on the gravel clasts. The oldest microlamination patterns observed in ultra-thin sections from sample location 2010 STF-6 are LU-1/LU-2/LU-3/LU-4 (WP2c), with an estimated age of 25·55 ka. Figure 4 shows the varnish microstratigraphy in samples 2010 STF-5 and 2010 STF-6.

Sample site 2010 STF-2 is located on a stable fan surface characterized by a well-developed pavement with rock varnish coating some of the cobbles and boulders. Small coppice deposits exist around desert shrubs. There is no pedogenic carbonate coating the undersides of half-buried cobbles and boulders, but iron oxide staining is common. The soil at this site contains a 5 cm thick, light yellowish-gray, very vesicular, upper Av horizon composed of moderately well consolidated clay, silt, and some fine to coarse sand with vesicles up to 5 mm, and a lower 4 cm thick, reddish-gray lower Av horizon composed of well consolidated clay, silt, and some sand with smaller and fewer vesicles, including small open horizontal partings near the bottom. An upper 11 cm thick, grayish red B horizon is composed of weakly consolidated silt, clay, and minor sand with very small (1–3 mm) clay nodules. This is underlain by a 10 cm thick lower B horizon composed of unconsolidated to very weakly consolidated sand, gravel, silt, and clay, with some carbonate coatings of gravel clasts. The oldest microlamination pattern observed in ultra-thin sections for 2010 STF-2 is LU-1/LU-2/LU-3/LU-4 (WP3e), with an estimated age of 35·75 ka.

Sample site 2010 STF-3 is located on a stable fan surface characterized by a well-developed pavement with areas of patterned pavement distributed generously about this particular fan surface. There is considerable desert varnish developed on the cobbles and boulders on this fan surface, and small coppice deposits associated with desert shrubs. While there is no pedogenic carbonate on the undersides of half-buried cobbles and boulders, red iron oxide staining is common and well developed. There is some bioturbation but it is restricted to widely spaced burrows of large burrowing animals. The soil at this site has a 5 cm thick, yellowish-gray to gray upper Av horizon composed of moderately consolidated clay, silt, and very minor sand, with abundant vesicles from 1 to 3 mm, and a 5 cm thick, reddish gray lower Av horizon composed of moderately consolidated clay, silt, and minor sand, with fewer vesicles from 1 to 4 mm and small open horizontal partings near the bottom. The reddish brown to brownish red upper B

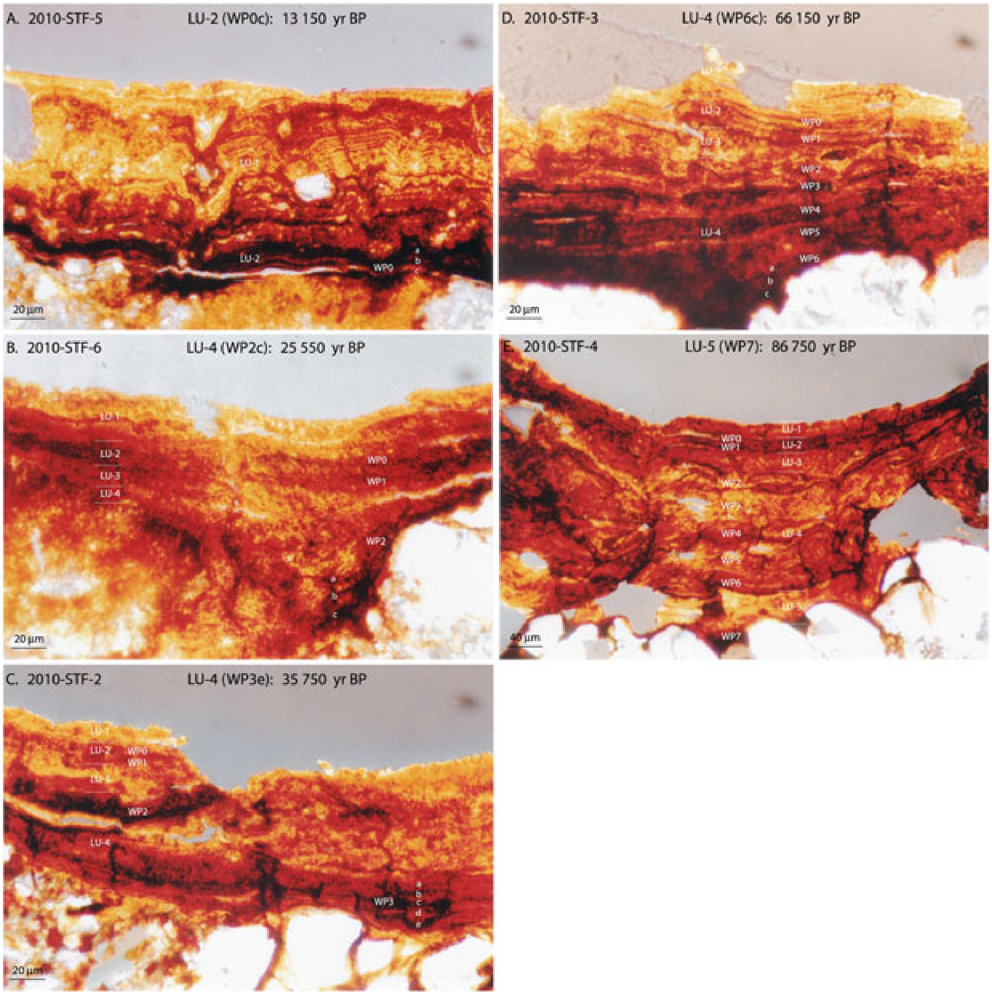

Figure 4. Optical microstratigraphies seen in ultra-thin sections display the dark and light laminations diagnostic of past wet and dry climate conditions, respectively. Photomicrograph of ultra-thin section 2010 STF-5 reveals an oldest VML stratigraphic record of LU-1/LU-2/(WP0c), yielding an age estimate of 13·15 ka. Photomicrograph of ultra-thin section 2010 STF-6 reveals an oldest VML stratigraphic record of LU-1/LU-2/LU-3/LU-4 (WP2c), yielding an age estimate of 25·55 ka. Photomicrograph of ultra-thin section 2010 STF-2 reveals an oldest VML stratigraphic record of LU-1/LU-2/LU-3/LU-4/(WP3e), yielding an age estimate of 35·75 ka. Photomicrograph of ultra-thin section 2010 STF-3 reveals an oldest VML stratigraphic record of LU-1/LU-2/LU-3/LU-4/(WP6c), yielding an age estimate of 65·15 ka. Photomicrograph of ultra-thin section 2010 STF-4 reveals an oldest VML stratigraphic record of LU-1/LU-2/LU-3/LU-4/LU-5(WP7), yielding an age estimate of 86·75 ka.

horizon is 4 cm thick and composed of well consolidated silt and clay with very minor coarse sand. The reddish brown lower B horizon is 4 cm thick, and composed of moderately consolidated silt, clay, minor coarse sand, and carbonate coated gravel clasts that increase in size and number downward. Below the B horizon the sediment consists of very weakly consolidated yellowish gray, gravel (up to 3 cm), sand, and silt. The oldest microlamination pattern observed in ultra-thin sections for 2010 STF-3 is LU-1/LU-2/LU-3/LU-4 (WP6c), with an estimated age of 65·15 ka.

Sample site 2010 STF-4 is located on a stable fan surface very similar to the surface at STF-3, with a well-developed pavement, some patterned pavement, well-developed varnish on the cobbles and boulders, and small coppice deposits formed only around the larger shrubs. The undersides of half-buried cobbles and boulders are stained with iron oxide, and shrinkage polygons are well developed in the clay-rich Av horizon beneath large flat boulders lying on the surface. The soil at this site has a 4 cm thick, yellowish-gray upper Av horizon composed of moderately consolidated clay, silt, and very minor sand, with vesicles up to 3 mm, and a 4 cm thick, reddish gray to medium gray lower Av horizon composed of very well consolidated to indurated clay, silt, small clay nodules (1–3 mm), and rare gravel clasts, with smaller and fewer vesicles and small open horizontal partings near the bottom. The reddish gray B horizon is 15 cm thick and composed of very well consolidated to indurated clay, silt, and some carbonate nodules and gravel clasts coated with carbonate. The sediment below the B horizon is composed of very weakly consolidated yellowish gray to light yellowish brown, clast-supported gravel, sand, silt, some clay. The oldest microlamination pattern observed in ultra-thin sections for 2010 STF-4 is LU-1/LU-2/LU-3/LU-4/LU-5 (WP7), with an estimated age of 86·75 ka. Figure 4 shows the photomicrograph of samples 2010 STF-2 and 2010 STF-3, and shows the photomicrograph of sample 2010 STF-4. Table V provides the varnish microstratigraphic nomenclature for the preserved laminations and the resulting age estimation for each VML sample location. Figure 5 shows the VML sample sites and age determinations superimposed on a satellite image of Stonewall Flat.

The VML age data and surface morphology descriptions from Stonewall Flat indicate a general maturing of stone pavements with increasing age, resulting in a decrease in the fine sediment between gravel clasts, increasing varnish development, and a general increase in the thickness and clay content of the Av horizon (Table VI). These results are counter to those reported by Parker (1995), who found a lower clay content and higher silt content in the older soils of the Ajo fan in Organ Pipe Cactus National Monument in the Sonoran Desert. Patterned

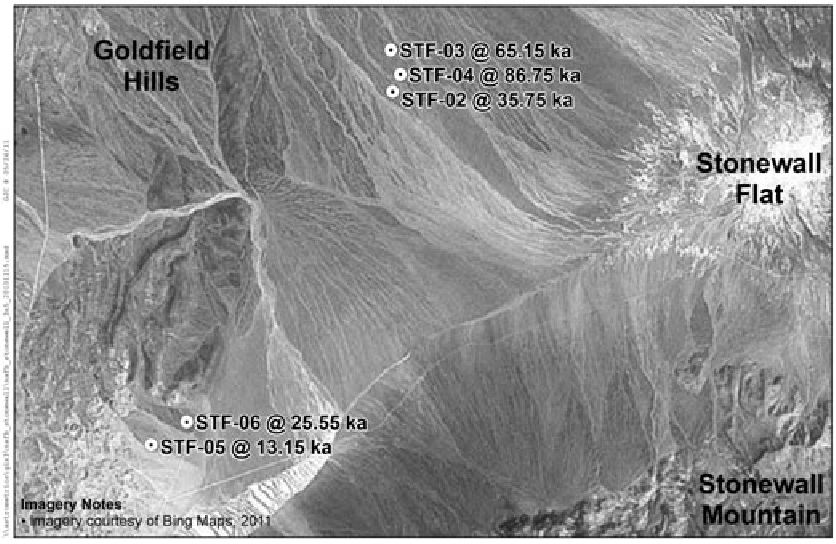

Figure 5. VML sample sites and age estimates for the Stonewall Flat alluvial fans.

Table V. VML age data.

Sample number	Number of ultra-thin sections	Observed microstratigraphic laminations (oldest on top)	VML age estimate
2010 STF-5	5	LU-1/LU-2(WPOc) (4) LU-1/LU-2(WPOb) (1)	13·15 ka
2010 STF-6	1	LU-1/LU-2/LU-3/LU-4(WP2c) (1) LU-1/LU-2/LU-3/LU-4(WP2) (1)	25·55 ka
2010 STF-2	3	LU-1/LU-2/LU-3/LU-4(WP3e) (1) LU-1/LU-2/LU-3/LU-4(WP3d) (1) LU-1/LU-2/LU-3/LU-4(WP3) (1)	35·75 ka
2010 STF-3	2	LU-1/LU-2/LU-3/LU-4(WP6c) (1) LU-1/LU-2/LU-3/LU-4(WP6) (2)	65·15 ka
2010 STF-4	3	LU-1/LU-2/LU-3/LU-4/LU-5(WP7) (1) LU-1/LU-2/LU-3/LU-4/LU-5(WP6+) (1) LU-1/LU-2/LU-3/LU-4(WP6d) (1)	86·75 ka

Table VI. VML ages, surface morphology, and soil development.

Site	Age (VML)	Surface	Soil
STF-5	13·15 ka	Relict bar & swale Pavement Some varnish Variable coppice Thermally cracked boulders	Upper Av – 5 cm, yellowish Lower Av – 3 cm, reddish, consolidated B – 13 cm, reddish, poor sort, very weak, with caliche & oxide coatings lower B-6 cm, reddish, weak, no coatings
STF-6	25·55 ka	Mature pavement w/gilgai Ubiquitous varnish Small coppice Thermally cracked boulders	Upper Av – 5·6 cm, yellowish Lower Av – 3 cm, reddish, hard B – 7 cm, reddish, weak Lower B – 5 cm, poor sort, weak, w/ caliche & oxide coatings
STF-2	35·75 ka	Mature pavement Small coppice Some varnish Oxide stains surface clasts	Upper Av – 5 cm, yellowish Lower Av – 4 cm, reddish, hard B – 11 cm, reddish, weak, w/small clay nodules Lower B – 10 cm, very weak, some caliche coatings
STF-3	66·15 ka	Mature pavement w/ gilgai Well developed varnish Small coppice Common oxide stain	Upper Av – 5 cm, yellowish Lower Av – 5 cm, reddish, consolidated B – 4 cm, reddish, hard Lower B – 4 cm, reddish, moderate consolidated, caliche coatings Below B – yellowish, poor sort, weak, caliche coatings
STF-4	86·75 ka	Mature pavement w/gilgai Well developed varnish Small coppice Common oxide stain	Upper Av – 4 cm, yellowish Lower Av – 4 cm, reddish, hard B – 15 cm, reddish, hard, caliche coatings Below B – yellowish, poor sort, very weak

pavements develop on surfaces with 9 cm or more of clay-rich Av horizon. Varnish appears to develop on boulders and larger cobbles first, and covers increasingly smaller clasts with increasing surface age. Soil profiles at all VML sites are older than 13 ka and have developed clay-rich Av horizons 8 cm or more thick. Each of these Av horizons exhibit two distinctive zones, a yellowish, less-well consolidated but very vesicular upper zone, and a reddish, more consolidated lower zone with fewer, smaller vesicles and open horizontal partings. B horizons at all five VML sites are reddened and contain gravel clasts exhibiting some degree of carbonate coating. The B horizons at the three sites younger than 36 ka are weakly consolidated whereas those at the two sites older than 66 ka are very well consolidated. The thickness of the both the A and B horizons varied in ways not necessarily correlative to increasing age.

It is worthwhile to point out that our VML data are consistent with the hypothesis that fan aggradation is an ongoing discrete sedimentational process occurring under various climatic conditions (Liu and Broecker, 2008a). For instance, varnish sample from site STF-5 contains a basal layer of WP0c with a VML age estimate of 13·15 ka, favoring fan aggradation during a time of late glacial climatic transition from wet to dry period (cf. Bull and Schick, 1979; Wells *et al.*, 1987). Those from sites STF-6 and STF-2/3 contain basal layers of WP2c, WP3e, and WP6c with VML age estimates of 25·55, 35·75, and 65·15 ka, respectively, supporting fan aggradation during the overall wet period of the last glacial time (cf. Ritz *et al.*, 2003; Owen *et al.*, 2006). Varnish sample from site STF-4 contains a basal layer of WP7 with a VML age estimate of 86·75 ka, making an argument for fan aggradation during the overall dry period of the last interglacial (cf. Chamyal *et al.*, 2003; Pope and Wilkinson, 2005). These pieces of evidence add new insights into a long-standing controversy in the southwest as to when alluvial fans undergo aggradational events, and suggest that different 'competing' hypotheses of alluvial-fan development may all be compatible, in part, with the available geomorphic, climatic, and geochronometric data.

Botanical survey results

A total of 42 species were sampled across 10 plots and only four non-native species were encountered. Table VII shows the estimated age/stability ranks and surface morphology of the sample surfaces. Total cover values for the 10 sample locations ranged from 11% to 54% and dominant species often differed from one sample location to another, as recorded in Table VIII.

There is no linear pattern where the plant communities on two surfaces of similar apparent age and stability consistently had the highest similarity scores. Instead, similarity scores

Table VII. Geomorphic characteristics of survey sites.

Plot ID	Rank	Sample date	Surface morphology
STF-34	1	13 June 2010	Active Wash
STF-36	2	13 June 2010	Older Abandoned Wash
STF-29	3	12 June 2010	Active Alluvial Fan Surface
STF-31	4	12 June 2010	Active Alluvial Fan Surface
STF-37	5	13 June 2010	Younger Terrace
STF-30	6	12 June 2010	Intermediate Alluvial Fan Surface
STF-35	7	13 June 2010	Stable Terrace
STF-33	8	13 June 2010	Older Intermediate Alluvial Fan Surface
STF-28	9	12 June 2010	Stable Alluvial Fan Surface
STF-32	10	13 June 2010	Stable Alluvial Fan Surface

Note: Geomorphological surfaces were sampled for vegetation cover and composition during June 2010. Sample sites are ranked in order of relative age and stability from the most recently active surface at the top to the most stable surface at the bottom. Relative age estimates are based on the surface characteristics discussed earlier. Ages of more stable surfaces corroborated with VML dates.

indicate a bimodal distribution where vegetation on the five assumed youngest and less stable surfaces are similar to one another but dissimilar to the vegetation on the five assumed oldest and more stable surfaces. This bimodal pattern remained unchanged even when the ranks of the plots with the three highest similarity scores to a given plot were averaged in an attempt to overcome natural stochastic variation in vegetative cover among plant communities. In fact, averaging the three highest ranks relative to each plot rank yielded mean ranks that tended toward the center of each the assumed younger or older group (Table IX).

The polar ordination visually confirms the clustering of sample plots into two fairly distinct groups (Figures 6 and 7). A comparison of ordination Axis 1 with Axis 2 results in a cluster of surfaces ranked as the five assumed youngest and less stable at the upper end of the scale on Axis 1 and centered along Axis 2. The surfaces ranked as the five assumed oldest and more stable occupy the lower end of Axis 1 and are spread across Axis 2 (Figure 6). Axis 1 can be interpreted as an analog for surface age and stability, as the plots sort out along the axis in a meaningful age and stability-related order when compared to conclusions from the Bray–Curtis similarity analyses (Table VIII). Axis 2 probably represents variability in site specific conditions that translate to plant community variability among the five assumed older and more stable surfaces. When ordination Axis 1 and Axis 3 are compared, the five assumed older and more stable surfaces form a distinct cluster at the lower ends of both axes, while the five assumed younger and more active surfaces are spread across Axis 3 (Figure 7). Thus, Axis 3 probably represents variability in site specific conditions that translate to plant community variability among the five assumed younger, more active surfaces.

A comparison of functional group cover among the 10 sample plots yielded information useful for understanding basic differences in species composition between the two plot groups identified in the multivariate analyses. Total vegetation cover tended to be higher on the five plots located on the assumed younger and more active geomorphic surfaces than on the five plots located on the assumed older and more stable geomorphic surfaces. Higher total cover values on plots from assumed younger, active surfaces appear to be a result of higher cover from annual species on those plots. Annual cover values were two-fold to three-fold higher on the plots from the assumed youngest, most active five surfaces, whereas perennial cover values were not substantially different between the two groups of plots (Figure 9). When functional group cover is normalized to total cover, it becomes apparent that the ratio of annuals to perennials is much higher on the plots from the group of assumed younger and more active surfaces. Conversely, perennial cover, which is primarily from shrub and sub-shrubs (Table VIII), dominates the relative vegetative composition of the five plots located on assumed older and more stable surfaces (Figure 8).

Discussion

Plant community development

Plant communities, as recognized by the dominance of characteristic species (e.g. FGDC, 2008), generally occur in a heterogeneous mosaic across the study area. Although vegetative cover and species composition within one or several related plant communities vary along a continuum, many transitions from one community type to another are quite abrupt and often coincide with transitions from one distinct alluvial fan or dry wash surface to another.

Table VIII. Percent absolute cover by species.

	STF-34	STF-36	STF-29	STF-31	STF-37	STF-30	STF-35	STF-33	STF-28	STF-32
Native perennial shrubs										
Atriplex canescens	0	5·64	1·88	0	0·54	0	0	0	0	0
Atriplex confertifolia	0	0	0	0	0	1·07	0	4·62	0·12	2·48
Chrysothamnus viscidiflorus	0	0	0	0	0	0·21	0	0	0	0
Ephedra funerea	0	2·5	0	6·3	0	1·44	0·18	8·48	0	1·84
Ericameria nauseosa	0	0	0	0	0	0·78	0	0	0	0
Grayia spinosa	0	0	0	4·74	0	4·04	14·76	4·72	5·81	4·66
Krascheninnikovia lanata	0	0	0	0	7·32	0	0	0	0	0
Picrothamnus desertorum	0	0	0	0	0·88	2·52	1·38	3·02	0	1·44
Native perennial sub-shrubs										
Bassia americana	0	0	0	0	0	0	1·08	0·38	0·7	0·68
Hymenoclea salsola	4·88	2·46	0	14·14	0	0	0	0	0	0
Lepidium fremontii	0	0·42	0	0·04	0·06	0·06	0·06	0·42	0	0
Stanleya pinnata	0	0	0	0	0	0·04	0	0	0	0
Native perennial graminoid										
Elymus elymoides	0	0	0	0	0	0	0	0·16	0	0
Native perennial forbs/herbs										
Arabis holboellii	0	0	0	0	0	0	0	0·28	0	0
Castilleja angustifolia	0	0	0	0	0	0·04	0	0	0	0
Chamaesyce albomarginata	0	0·16	0	0	0	0	0	0	0	0
Cryptantha tumulosa	0·14	0	0	0	0	0	0·06	0·08	0	0
Descurainia pinnata	0·18	0·44	0	0·58	0·2	0	0·06	0	0	0
Sphaeralcea ambigua	0·44	0	0	0·1	0	0	0	0	0	0
Stephanomeria parryi	0	0·14	0	0	0·02	0	0	0	0	0
Tiquilia plicata	0	0	0·39	0	0	0	0	0	0	0
Native annual forbs/herbs										
Aliciella leptomeria	0·12	0·52	0·58	0·06	0·38	0·04	0·18	1·92	0·09	0·16
Ambrosia acanthicarpa	0	0	0·06	0	0	0	0	0	0	0
Amsinckia tessellata	0·18	0	0	1·38	0	0	0	0	0	0
Camissonia boothii	0·12	0	0	0·02	0	0·06	0	0·6	0	0
Camissonia minor	0·24	0	0	0	0·1	0	0·46	0	0	0
Chaenactis stevioides	2·54	7·62	19·71	10·89	12·46	0·46	1·22	3·32	0·52	0·04
Chorizanthe rigida	0	0	0	0	0	0	0·02	0·12	0	0
Cryptantha circumscissa	0	0	0·2	0·1	0·36	0	0·24	0·08	0	0
Eriastrum sparsiflorum	0	0	0·24	0	0	0·04	0	0	0·13	0
Eriogonum deflexum	7·48	1	1·7	0·98	0	0	0·02	0·04	1·73	0
Ipomopsis polycladon	0	0	0	0	0	0·14	0	0	0	0
Langloisia setosissima	0·02	0·02	0	0	0·02	0	0·04	0	0	0
Lepidium densiflorum	0	0	0	0	0	0	0	0·06	0	0
Malacothrix glabrata	0	0·06	0	0·96	0·24	0	0	0	0	0
Mentzelia albicaulis	0·48	5·06	5·08	12·08	2·98	0	0	0	1·58	0
Oxytheca perfoliata	0	0·46	0	0	0	0	0·06	0·74	0	0·1
Phacelia fremontii	0	0·08	0·18	0·02	0	0	0·08	0·58	0·06	0
Introduced annual graminoid										
Bromus rubens	0·04	0	0	1·44	0·02	0·1	0	0·42	0	0·14
Introduced annual forbs/herbs										
Amaranthus albus	0	0	0·2	0	0	0	0	0	0	0
Halogeton glomeratus	0	0	0·04	0	0	0	0	0	0	0
Salsola tragus	0·1	0·08	0	0·14	0·76	0	0	0	0	0

Note: Percent absolute cover by species from line interception data collected on 10 vegetation transects in Stonewall Flat. Plots are arranged based on relative geomorphic age, from the most recently active (left) to the most stable for the longest period of time (right).

Table IX. Floristic composition relationships among transects.

	Rank	Plot with highest BC score	Rank of plot with highest BC score	BC score	Mean top three ranks
STF-34	1	STF-36	2	0·32	3·0
STF-36	2	STF-29	3	0·57	4·0
STF-29	3	STF-37	5	0·59	3·7
STF-31	4	STF-36	2	0·48	3·3
STF-37	5	STF-29	3	0·59	3·0
STF-30	6	STF-32	10	0·72	9·0
STF-35	7	STF-28	9	0·47	9·0
STF-33	8	STF-32	10	0·54	6·7
STF-28	9	STF-32	10	0·5	7·7
STF-32	10	STF-30	6	0·72	7·7

Note: The complement of the Bray–Curtis (BC) score of dissimilarity was used to compare floristic composition among plots. Mean top three ranks refer to the average rank of the three plots with the highest similarity scores to a given plot.

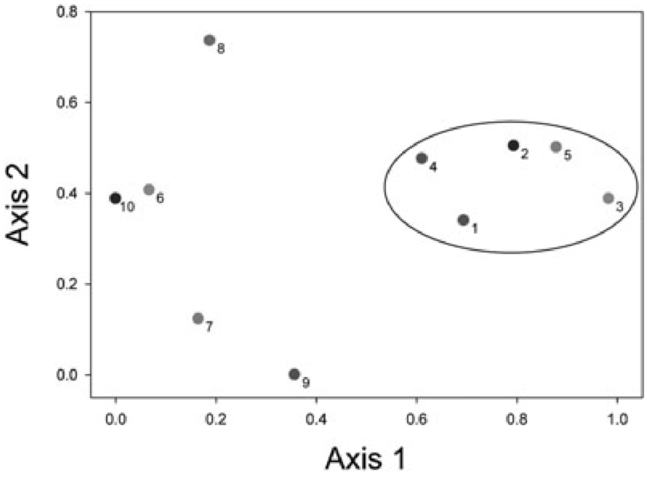

Figure 6. Axes 1 and 2 of a Bray–Curtis ordination plot depicting floristic similarity among plots sampled on surfaces of various ages at Stonewall Flat during June 2010. Plots are ranked in order of relative age, from the most recently active surface to the surface which has been stable for the longest time period.

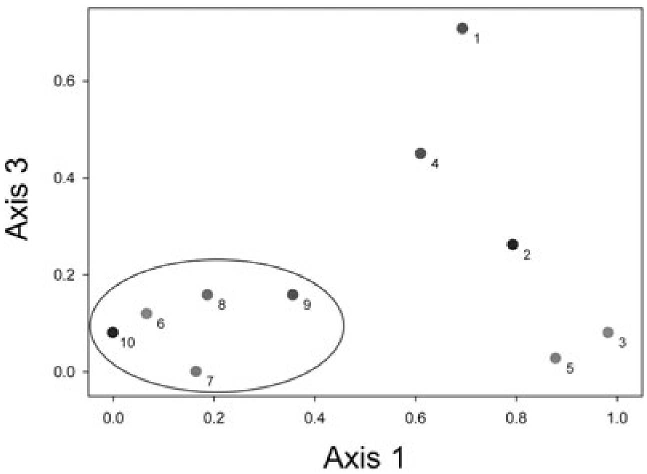

Figure 7. Axes 1 and 3 of a Bray-Curtis ordination plot depicting floristic similarity among plots sampled on surfaces of various ages at Stonewall Flat during June 2010. Plots are ranked in order of relative age, from the most recently active surface to the surface which has been stable for the longest time period.

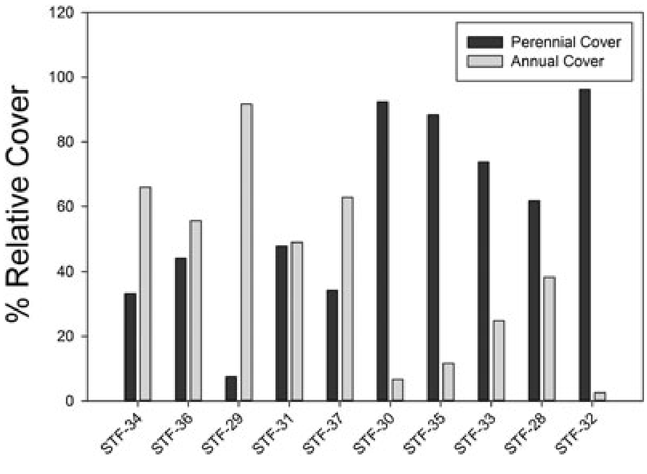

Figure 8. Percent relative cover for native vegetation functional groups sampled on surfaces of various ages at Stonewall Flat during June 2010. Plots are ranked in order of relative age, from the most recently active surface on the left to the oldest and most stable surface on the right.

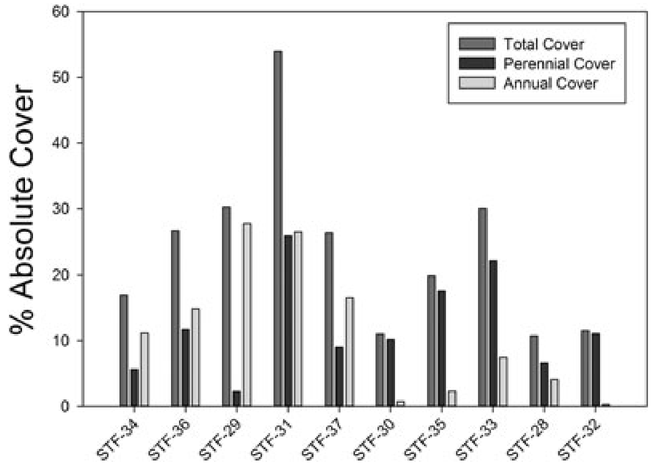

Figure 9. Percent absolute cover for native vegetation functional groups sampled on surfaces of various ages at Stonewall Flat during June 2010. Plots are ranked in order of relative age, from the most recently active surface on the left to the oldest and most stable surface on the right.

Furthermore, the spacing of vegetation within the boundaries of a given geomorphic surface appears to be related to the relative age of that surface. For example, distinct coppice/ interspace, or clumped spatial patterning, is evident on mature alluvial fan and terrace surfaces with well-developed desert pavement, which is characteristic of the older surfaces (Smith *et al.*, 1997). Conversely, younger surfaces exhibit some coppice formation associated with shrubs, but interspaces between the coppices are much less distinct and contain abundant herbaceous biomass, resulting in a more random spatial vegetation pattern.

Overall, species that dominated at least one plot were generally present in several other plots (Table VIII), indicating that the pool of species availability is somewhat constant across the study area. This pattern suggests that many abiotic factors like nutrient levels, salinity, alkalinity, and such were not highly variable between survey locations, since large variation in abiotic conditions favors assemblages of unique species. Because differences in plant communities were defined more by proportional abundances than by the occurrence of unique species, the surfaces sampled likely also had similar gross soil characteristics in terms of composition, compaction, depth, and water-holding capacity. This is supported by observational data collected from soil pits on various surfaces. Therefore, the age and stability of the surface sampled is probably one of the primary factors influencing vegetation composition. The notable exception for unique species occurrences is winter fat, which occurred with abundance in the plant community at STF-37, but was not present with enough abundance to have been sampled at the other survey sites. This young terrace was ubiquitously bioturbated from burrowing animals at the survey site, which resulted in unusually loose soil of sand and gravel unique among all the survey sites.

The Bray–Curtis similarity scores suggest that the plant communities on younger and more active surfaces were similar to one another, and plant communities on older and more stable surfaces were similar, but plant communities on younger and more active surfaces were demonstrably dissimilar to those on older and more stable surfaces. In general, the emergence of two distinct age and stability-based clusters across the three ordination axes supports the interpretation of plant communities belonging to two distinct age groups rather than forming a linear progression of community relatedness from younger/ active to older/stable surfaces. Annual species contributed the greatest proportion of vegetative cover on the younger surfaces, and woody species contributed the greatest proportion of vegetative cover on the older surfaces. Similar results are reported by McAuliffe (1994) and Parker (1995), who found higher species diversity on more unstable fan surfaces in the Sonoran Desert, and woody shrubs dominating the more stable fan surfaces.

Although annuals have long been described as 'colonizers' in plant communities where soils have been disturbed, they have also been found to function as ephemerals in desert ecosystems (Smith *et al.*, 1997). These two concepts are not mutually exclusive; the first implies that annuals fill a specific role in a mechanistic temporal progression of plant communities while the second suggests that annual species abundance fluctuates dynamically in response to resource availability. In the Stonewall Flat area, woody species are poorly represented in active washes, where surface disturbance is ongoing and occurs with enough regularity so as to prevent their establishment, results similar to those of McAuliffe (1994) and Parker (1995) in the Sonoran Desert. Otherwise, the absolute cover of woody species does not appear to be strongly related to surficial age and stability, and we observed that annuals were found on plots across all surface age groups in varying abundances (Table IX). Taken together, these patterns suggest that annuals are functioning primarily as ephemerals rather than as 'pioneers' across the study area. Because ephemerals germinate and utilize spring moisture only in years when it is available, the distribution of annuals in any given year is likely to be highly variable and not necessarily a reliable indicator of the age or stability of a geomorphic surface.

These results are somewhat analogous to the findings of Parker (1991), who observed botanical communities associated with rocky slopes distinct from those associated with bajada and fan surfaces in the Sonoran Desert. In both Stonewall Flat (this study) and the Sonoran Desert (Parker, 1991, 1995), changes in the botanical communities are associated with changes in soil type. However, the variable identified by Parker (1991, 1995) as controlling the changes in soil characteristics is slope, with steeper slopes yielding coarser and more poorly sorted soils compared to the soils associated with the relatively flatter bajada and fan surfaces. In contrast, the slope of the fan surfaces in Stonewall Flat are less variable and the age and corresponding dominance of primary versus secondary fan processes manifests a greater control on soil development and associated plant communities. The Stonewall Flat study did not investigate nutrient variability in the soils, as did a study of arid fan soils in the Sonoran Desert by Parker (1995). However, our results of the physical characteristics of the fan soils and their strong affect on plant distribution is congruent with the smaller effect of nutrient distribution on plant distribution relative to the effects of physical soil characteristics reported by Parker (1995).

The relative dominance of annual species on the younger surfaces in this study likely relates to favorable conditions for germination that resulted from a sample year with abundant spring moisture. Annuals in Stonewall Flat occurred more often in the interspaces between shrubs on younger surfaces than in interspaces between the shrubs and coppices on older surfaces where pavements are well-developed. Desert pavements have been documented to have very low infiltration rates, high sodium content, and a lack of fine material available at the surface, making surface conditions unfavorable for germination and establishment (Smith *et al.*, 1997). Therefore, annual cover is likely highest on younger surfaces where physical and chemical soil properties are more favorable for establishment across the entire surface than they are on older surfaces where favorable soil properties are restricted to coppices. Thus, soil development appears to restrict the distribution of annuals in very mature plant communities, even when spring precipitation is adequate. In other words, if annuals establish opportunistically where conditions are favorable, there are simply fewer favorable conditions on surfaces with well-developed desert pavements.

While the distribution of annual species appears to be related to soil development as a function of surface age and stability, a shift in the composition of woody species through time is more likely associated with traits inherent to individual species. The identity of the most abundant perennial species for each sample site differed between the younger and older surfaces. Burrobush and fourwing saltbush tended to be the most abundant perennial species on plots sampled among the five younger and more active surfaces, while Death Valley jointfir and spiny hopsage were the most abundant perennial species among the five oldest and most stable surfaces (Table IX). Some researchers have documented a transition from short-lived shrubs and sub-shrubs to longer-lived woody species as a function of time since surface disturbance (Webb *et al.*, 1987; Bowers *et al.*, 1997). These researchers propose that life history characteristics, such as growth rate and seed production of the dominant species, control the distribution of woody species across surfaces of varying ages and stabilities. Others have suggested that nearly 1000 years may be required for the establishment of mature and stable plant communities dominated by long-lived woody species in warm desert ecosystems (Smith *et al.*, 1997). McAuliffe (1994) indicates that age-related soil development controls moisture infiltration and water availability. This, in turn, effects the composition of the botanical communities established on the more stable surfaces.

Geomorphic fan development and biotic feedback

Incised channel floods and sheet floods are the primary processes most likely to dominate Stonewall Flat because the local precipitation patterns favor flash floods, and local relief does not favor the gravity-driven processes. Active fan surfaces adjacent to fan channels exhibit surface features characteristic of primary and secondary fan processes. The sediments composing these surfaces are dominated by felsic volcanic rocks from the surrounding mountains. The homogeneity of the resulting sediments yields fairly uniform soil characteristics of salinity, alkalinity, and moisture retention that diminishes variation in the plant communities based on divergent soil types.

The youngest geomorphic surfaces in the study area are the active washes in the canyons surrounding Stonewall Flat and on the fans surrounding it. Primary sedimentation here is dominated by infrequent, high-energy floods, with more frequent runoff events adding moisture that favors botanical communities dominated by annuals. The resulting surfaces contain coarse sand, gravel, and cobbles in bars and swales. Early plants on relatively active fluvial and fan surfaces typically trap sand on their lee side, which provides a favorable environment for microbiotic soil crust development. These filamentous cyanobacteria and green algae colonize the sandier portions of the surface, stabilizing sandy surface soils, trapping moisture, and fixing nitrogen that assists the germination and growth of additional annuals and perennials alike (West, 1990). Such concentrations of plants trap additional fine sediment from sheet-flow and eolian processes. Although flash floods on the more active channel surfaces easily disrupt these finer-grain surface deposits, increasing surface stability allows them to host ever more robust assemblages of plants.

As channel surfaces are abandoned by channel migration, a thin veneer of silt and sand are deposited on the cobble bars and gravel swales by lower-velocity overbank flooding. These sandier surface sediments promulgate the growth equally of woody perennials and annuals, but only the woody shrubs persist year to year through relatively wet and dry weather cycles. Eolian processes become more prominent with increasing surface stability as the wind erodes silt and fine sand from sparsely vegetated areas and transports it laterally to the wind shadow at the base of these shrubs. These coppices in turn, support higher concentrations of annuals which assist in trapping additional eolian sediment. Bioturbation from burrowing animals typically is concentrated in these coppice deposits where it mixes the fine and coarse sediment. However, the interspaces between these early coppices are much less distinct and contain abundant herbaceous biomass, resulting in a more random spatial vegetation pattern on these relatively younger and more active surfaces.

The intermediate fan surfaces are viewed here as transitional from primary high-energy depositional geomorphic processes to secondary lower-energy surface modifying geomorphic processes. Gravel is concentrated on the surface as sheetwash winnows out silt and sand (Williams and Zimbelman, 1994). The coppice deposits that developed early around most shrubs slowly diminish in size through deflation until only the largest shrubs host small coppices. On older and more stable surfaces coppice deposits contain the only unconsolidated surface sediment available to plants and small burrowing animals for bioturbation, resulting in the germination of additional plants. Thus, shrubs and sub-shrubs that initially grew opportunistically on relatively active surfaces generally favorable everywhere for their growth, thrive at locations on older and more stable fan and terrace surfaces due to surface sediment patterns they themselves contributed to. These coppices, by attracting burrowing insects and small animals and providing a favorable environment for annuals and perennials, form local ‘resource islands’ for desert plants and animals on surfaces dominated by pavements otherwise unfavorable to them (Clifford and Gosz, 1982).

The terrace and younger intermediate fan surfaces develop the first real pavements and cumulate soil horizons by trapping eolian clay and dust between and beneath the gravel clasts (McFadden *et al.*, 1987). These pavements develop primarily in the interspaces between the shrubs and their associated coppices. As pavements mature and thick, well consolidated Av horizons develop, the surface becomes ‘armored’ against the germination and growth of ephemeral plants. This bimodal surface of pavement and coppice is reflected in a bimodal distribution of plants between the relatively barren pavements and the relatively productive ‘resource island’ coppices, as well as the composition of the botanical community itself.

The coppices on the older, more stable fan surfaces of Stonewall Flat manifest similar morphologies to the plant scar mounds illustrated in figure 6A and 6B of McAuliffe and McDonald (2006), but do not achieve a similar size to those described for the fan surfaces in the Sonoran Desert at the US Army Yuma Proving Ground (YPG). Similarly, plant scar depressions similar to those described at the YPG (McAuliffe and McDonald, 2006) are entirely absent from the fan surfaces in Stonewall Flat. As the alluvial fans at both locations are otherwise quite similar in their development of stone pavements, cumulate soils, and overall plant density, we speculate that the difference exists in certain biologic feedback mechanisms in place at each location. The coppice deposits (plant scar mounds) described for the YPG are much larger (2–6 m in diameter and 25 cm high) than those observed on Stonewall Flat (typically $<$ 1·5 m in diameter and $<$ 15 cm high). Furthermore, the plant scar mounds at the YPG appear to be much more thoroughly mixed by bioturbation than those on Stonewall Flat, which are overwhelmingly dominated eolian-derived fine sand. Thus, it appears that burrowing animals are much more prevalent, and their activities much more concentrated in the coppice deposits of on the YPG than they are in Stonewall Flat. In contrast, the eolian-dominated coppice deposits on Stonewall Flat diminish in size with age through ablation rather than develop into plant scar depressions via the processes described by McAuliffe and McDonald (2006). This supposition is supported by observations by the senior author of much larger plant scar mounds very similar in size and character to those described by McAuliffe and McDonald (2006) in higher alluvial basins of the NTTR where increased precipitation appears to support a larger population of small animals than occurs in Stonewall Flat.

Conclusion

In Stonewall Flat, south-western Nevada, USA, active and abandoned washes in canyons and alluvial fans are younger surfaces dominated by primary processes characterized by the punctuated, high energy, fluvial deposition of flashing channel floods and sheet floods. These surfaces are characterized by bar and swale topography, a lack of stone pavements, soil horizons, and rock varnish. Older abandoned wash surfaces, younger terraces, and intermediate fan surfaces are transitional from being dominated by primary processes to being dominated by secondary processes, which typically are lower energy but more frequent events involving sheet flow and eolian erosion, transport, and deposition, soil development, and bioturbation. These surfaces are characterized by faint to no bar and swale topography, incipient to moderately well-developed pavements and soil horizons, abundant coppices, desert varnish limited to boulders and larger cobbles, and microbiotic soil crusts. Older terraces and stable fan surfaces are dominated by secondary processes and manifest well-developed pavements, soils, and varnish, with sparse coppices around widely distributed shrubs. Varnish microlamination age data indicates that the older intermediate fan surfaces are around 13·15 ka, while the older and fully stabilized fan surfaces range in age from 25·55 to 86·75 ka.

Communities of desert plants change with fluvial channel and alluvial fan surfaces in arid landscapes. Overall, there was no one individual species or group of species that can be used as a reliable indicator of surficial age and stability. However, the spatial distribution of species on various desert surfaces coupled with life history traits of the dominant species are useful for understanding the interplay between geomorphic processes, relative surface age and stability, and biotic/abiotic feedback mechanisms. The composition of the plant communities associated with these arid surfaces has a distinctly bimodal distribution. The younger and more active surfaces in both canyon bottom settings and alluvial fan settings are dominated by flowering annuals, which fulfill the role of ephemeral plants responding to periods of abundant moisture. The older and more stable surfaces characterized by coppices and interspaces covered with stony pavements are dominated by woody shrubs and sub-shrubs, but also contain annuals. The older surfaces containing well-developed pavements also manifest a distinctly bimodal spatial distribution of plants, with most perennial shrubs as well as annuals confined to coppices, and sparsely vegetated pavement-covered interspaces. In these settings, the coppices act as resource islands supporting a variety of burrowing insects and animals, and much more favorable for the germination of annuals than the pavements.

Feedback mechanisms between surface-modifying geomorphic processes and plant growth and distribution manifest early when plants in active and recently abandoned washes trap sandy sediment in their lee. Sandier sediments promote microbiotic soil crusts, and favor early germination of a variety of plants. Higher plant densities in heterogeneous botanical communities promotes coppice development, which is self-reinforcing as enhanced germination and growth in the softer surface sediment promulgates additional eolian deposition. On older stable surfaces coppice deposits contain the only unconsolidated sediment favorable to plants and small burrowing animals. Shrubs that initially grew opportunistically on more active surfaces thrive on more stable surfaces due largely to surface sediment patterns they contributed to.

Several observations drawn from this investigation may prove useful for using plant communities to estimate a general time period since the last surface-disturbing activity, such as a flash flood or debris flow. (1) Species assemblages containing very little cover from woody species tend to be located on surfaces that are more active. (2) The co-dominance of shrub and annuals with an abundance of annuals in areas between the shrubs is indicative of a surface that is transitional between higher energy but less frequent primary processes and lower energy but more frequent secondary processes, though this pattern may be less detectable in dryer than average years due to a paucity of annuals. (3) The dominance of long-lived woody species like Death Valley jointfir and spiny hopsage suggest that debris flow or flash flood has not occurred in several centuries. (4) Plant communities that exhibit low variability in total vegetative cover from one year to the next due to the development of a stable desert pavement are indicative of very old surfaces for which enough time has passed to allow significant pavement and Av soil development, resulting in the restriction of germination and establishment of annual species.

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