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URBAN GEOMORPHOLOGY

LANDFORMS AND PROCESSES IN CITIES

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CHAPTER

10

Urban Geomorphology of an Arid City: Case Study of Phoenix, Arizona

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OUTLINE

10.1 SONORAN DESERT SETTING OF THE PHOENIX METROPOLITAN AREA

The present-day climate and vegetation of the Phoenix metropolitan region (Fig. 10.1) resembles much of the rest of the Sonoran Desert in central Arizona, USA. Annual precipitation displays a bimodal distribution with summer and winter maxima. Summer convective thunderstorms occur during the July–September Mexican Monsoon. Winter frontal rainfall derives from Pacific cyclones. Mean annual precipitation tends to be evenly split between winter and summer, averaging about 200 mm (Arizona State Climatologists office, https://azclimate.asu.edu/). The arid climate is typified by a distinct biogeography typical of the

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FIGURE 10.1 **The state of Arizona as seen in Google Earth.** The *black box* identifies the metropolitan Phoenix region as framed in Fig. 10.2. The *dashed line* indicates the boundary of the Sonoran Desert, where Phoenix is situated in the northeastern corner. The forested highlands of the Mogollon Rim to the northeast provide much of the water for metropolitan Phoenix, funneled by the Verde and Salt River drainages. *Source: The image is used following permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html).*

Sonoran Desert. Trees include palo verde (*Parkinsonia microphylla*), ironwood (*Olneya tesota*), and elephant tree (*Bursera microphylla*). Common desert scrub vegetation includes creosote bush (*Larrea tridentata*), brittlebush (*Encelia farinosa*), triangle-leaf bursage (*Ambrosia deltoidea*), catclaw acacia (*Acacia greggii*), desert globe mallow (*Sphaeralcia ambigua*), and ocotillo (*Fouquieria splendens*). Succulents occur in great variety, notably the iconic saguaro (*Carnegiea gigantea*), barrel (*Ferocactus cylindraceus*), and hedgehog (*Echniocereus engelmannii*) cacti that are abundant throughout the natural landscape.

Pollen and packrat midden studies in the Sonoran Desert and adjacent areas suggest the region did not become a desert until the Holocene and it was not a desert during the Pleistocene. Pollen records in northern Baja California from 44 to 13 ka reveal the presence of pines, junipers, and sagebrush in that area indicating more humid and cooler conditions

(Lozano-García et al., 2002). Packrat midden sequences in the Sonoran Desert indicate the presence of the dwarf conifers *Juniper osteosperma* and *Pinus monophylla* in the lower Sonoran Desert in this same late Pleistocene time range (Allen et al., 1998; McAuliffe and van Devender, 1998; van Devender, 1990). Thus, abundant evidence of a wetter and cooler time generated more extensive vegetation in the last glacial period and perhaps previous glacial cycles.

The geology of the Phoenix area underwent major crustal extension during the mid-Tertiary. This crustal extension resulted from the release of compressional stress after the Laramide mountain building period (Coney and Harms, 1984; Holt et al., 1986; Nations and Stump, 1981). This extension generated basin and range topography that developed between about 25 and 8 Ma. As a part of this extension, major rhyolite caldera eruptions started about 20 Ma, and metamorphic core complexes also domed up before most volcanic activity and extension finally ceased around 8 Ma (Reynolds, 1985; Spencer, 1984). The net result is a bedrock geology that mixes intrusive igneous granitic rocks, foliated metamorphic blocks, as well as extensive outcrops of rhyolitic welded tuff from major eruption episodes during extension (Fig. 10.2).

The geomorphic landscapes of the Phoenix area contain a mixture of classic desert landforms. Bedrock landforms depend greatly upon the rock type. Granitic forms include classic domed inselbergs or bornhardts where jointing is far apart, but more complex landscapes where the jointing density increases and influences biotic communities (Seong et al., 2016b). Metamorphic slopes tend to host debris-flow chutes and levees (Dorn, 2012). Rhyolitic welded tuff deposits of the Superstition volcanic field (Stuckless and Sheridan, 1971) develop more massive cliff faces.

The nature of piedmont slopes in front of the ranges depends on drainage area. Larger ranges have sufficient drainages to develop alluvial fans or alluvial slopes (Applegarth, 2004), whereas bedrock pediments form in front of smaller mountain masses (Kesel, 1977). The low-relief areas now occupied by the urbanscape of the Phoenix metropolitan area (Fig. 10.2) consist of the distal ends of pediments, the distal end of alluvial fans, aeolian sand sheets, and alluvial deposits.

An individual walking on these landforms, before massive land-use change associated with cattle grazing and urban expansion, would have experienced very different surface conditions than found by the average hiker today. Extensive areas once hosted desert pavements, biological soil crusts (Nagy et al., 2005), and interlocking colluvium on steeper slopes, providing a net armoring effect (Bowker et al., 2008; Granger et al., 2001; Seong et al., 2016a). Today, only patches of such armored surfaces remain, providing glimpses into the original land surfaces. Thus, this chapter attempts to give the reader a sense of the geomorphology that once was (and still exists in a few places) and a desert geomorphology influenced by the Anthropocene (Waters et al., 2016) and its urban footprint.

10.2 COMMON DESERT GEOMORPHIC PROCESSES IN THE PHOENIX METROPOLITAN AREA

This section presents some of the more important desert geomorphic processes that occur in the Phoenix area. The section starts with processes related to rock decay (weathering) (in general, we prefer the use of the term rock decay instead of weathering for reasons elaborated elsewhere; Hall et al., 2012), rock coatings, and soils. The second section explores how aeolian,

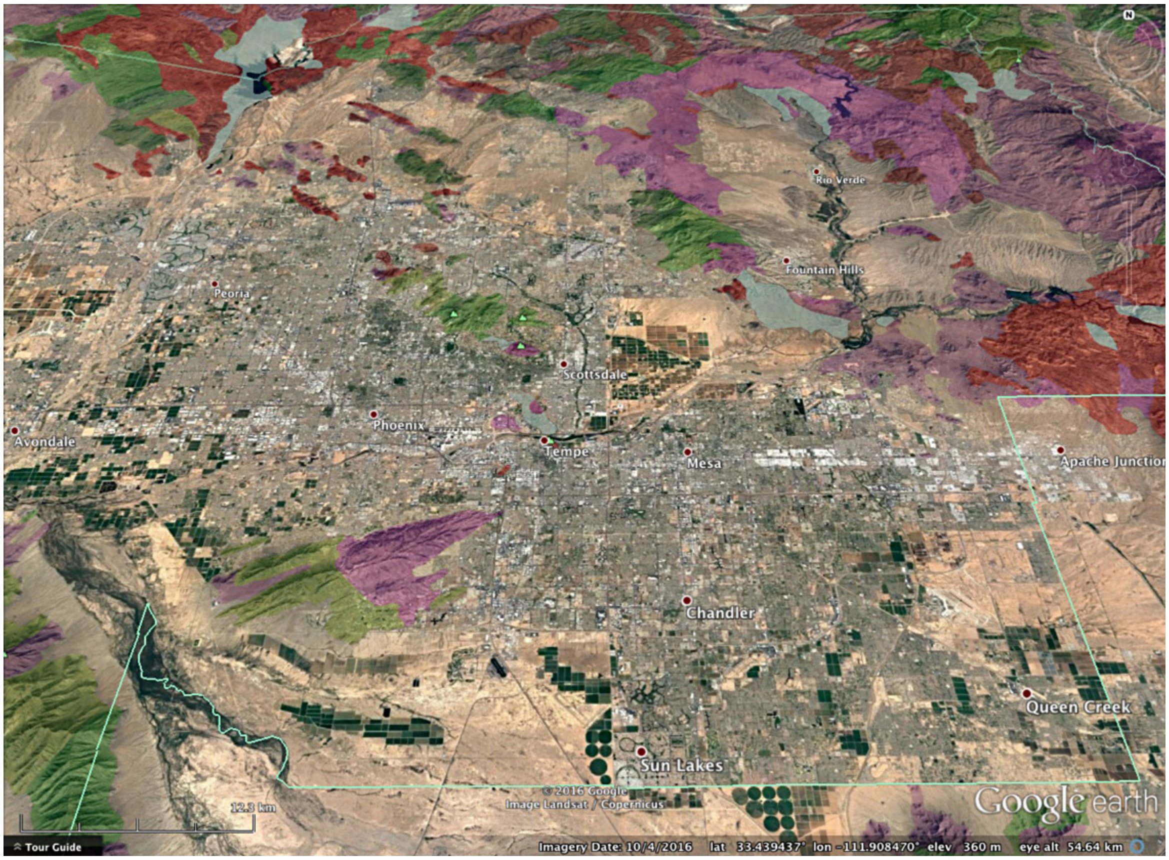

FIGURE 10.2 **Geological map of bedrock ranges in the metropolitan Phoenix overlaid on a Google Earth oblique image.** The mapping units derive from the Arizona Geological Survey (Richards et al., 2000), but are generalized here to help visualize isolated bedrock mountainous areas: intrusive igneous (pink), extrusive igneous (red), metamorphic (green), and mid-Tertiary sedimentary rocks (gray). Most urban space, thus, rests on Quaternary sediment ranging from Pliocene to Holocene in age. *Source: The image is used following permission guidelines for Google Earth to Source: The image has been modified from a Google Earth image (http://www.google.com/permissions/geoguidelines.html) with mapping units derived from Richards, S.M., Reynolds, S.J., Spencer, J.E. Pearthree, P.A., 2000. Geologic Map of Arizona. Arizona Geological Survey Map M-35, 1 sheet, scale 1:1,000,000.*

fluvial, and human activities interact in the fringe of the Phoenix urban area. The third section overviews mass-wasting processes on the steep slopes of desert mountain ranges in the middle of Phoenix. Much of the Phoenix metropolitan region is built on pediments and the fourth section explains that the Phoenix area is truly unique in terms of the occurrence of pediments in several different rock types.

10.2.1 Rock Decay, Rock Coatings, and Soils

10.2.1.1 Dominant Rock Decay Process

Dirt cracking is the dominant process of physical rock decay in the Phoenix area. Any random rock fracture, when pried open, reveals evidence of the dirt-cracking process

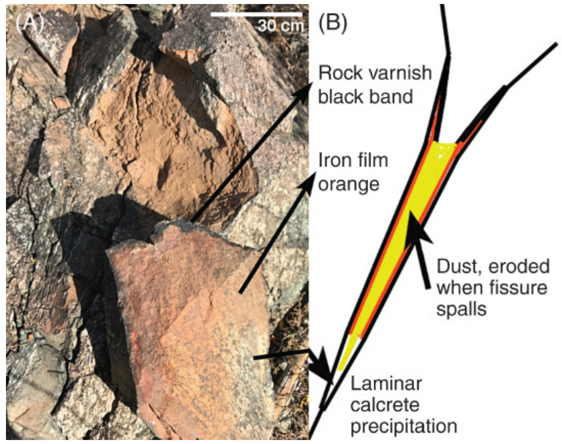

FIGURE 10.3 **Dirt cracking wedges open joint faces in two ways: laminar calcrete precipitation and the wetting and drying of dust in the joints.** (A) A 0.5 mm fracture was manually pried open at South Mountain, Phoenix. Dust filled the fracture. The two sides of the fracture display rock coatings diagnostic of dirt cracking. (B) Idealized diagram of rock coatings associated with fractures opened by dirt cracking.

(Dorn, 2011; Ollier, 1965). A combination of laminar calcrete precipitation and the wetting and drying of dust accumulated in fractures gradually opens fissures to the point where spalling occurs. Unlike other forms of physical rock decay, dirt cracking leaves behind visual evidence of the process (Fig. 10.3). Laminar calcrete coats the walls along the narrowest parts of a fissure, which is a space wide enough for capillary water to penetrate and precipitate calcium carbonate. Eventually, the fracture widens enough to allow dust to infiltrate. Iron (Fe) films typically less than 10 μm-thick coat the walls, where dust remains in contact with rock surfaces. Black rock varnish forms a rim around the margins of the fracture, where rainwater has washed away the dust and the removal of this alkaline dust allows manganese-enhancing bacteria to develop and form a coating of rock varnish over the Fe film.

10.2.1.2 Granitic Landforms Generated by Rock Decay

Granitic rocks underlay extensive areas of metropolitan Phoenix (Fig. 10.2). Thus, classic forms of cores stones, tors, domed inselbergs (bornhardts), and kopje occur throughout the Phoenix area (Fig. 10.3). Jointing is particularly important in the morphogenesis of granitic terrains: "Here we speculate that a corollary to the arguments given above about the role of tectonics as a crusher of rock is that in those places where rock has dodged the rock crusher, it may be stronger and less easily removed by erosive agents" (p. 10) (Molnar et al., 2007). Jointing is particularly important in arid weathering-limited landscapes (Abrahams et al., 1985; Howard and Selby, 2009; Viles, 2013).

Core stones and tors are common in the wealthier areas of metropolitan Phoenix, such as north Scottsdale, Fountain Hills, and east Mesa. Core stones are the spheroidal less-decayed boulders that emerge at the surface as grus erodes (Fig. 10.4B) (Twidale, 1982). Domed inselbergs, also known as bornhardts, are bald, and steep-sided domes with a range of shapes and size (Twidale, 1981) (e.g., Fig. 10.4A). Bornhardts like those seen in metropolitan Phoenix (e.g., Fig. 10.4A) maintain a lower joint density than the surrounding granite. Meanwhile, the

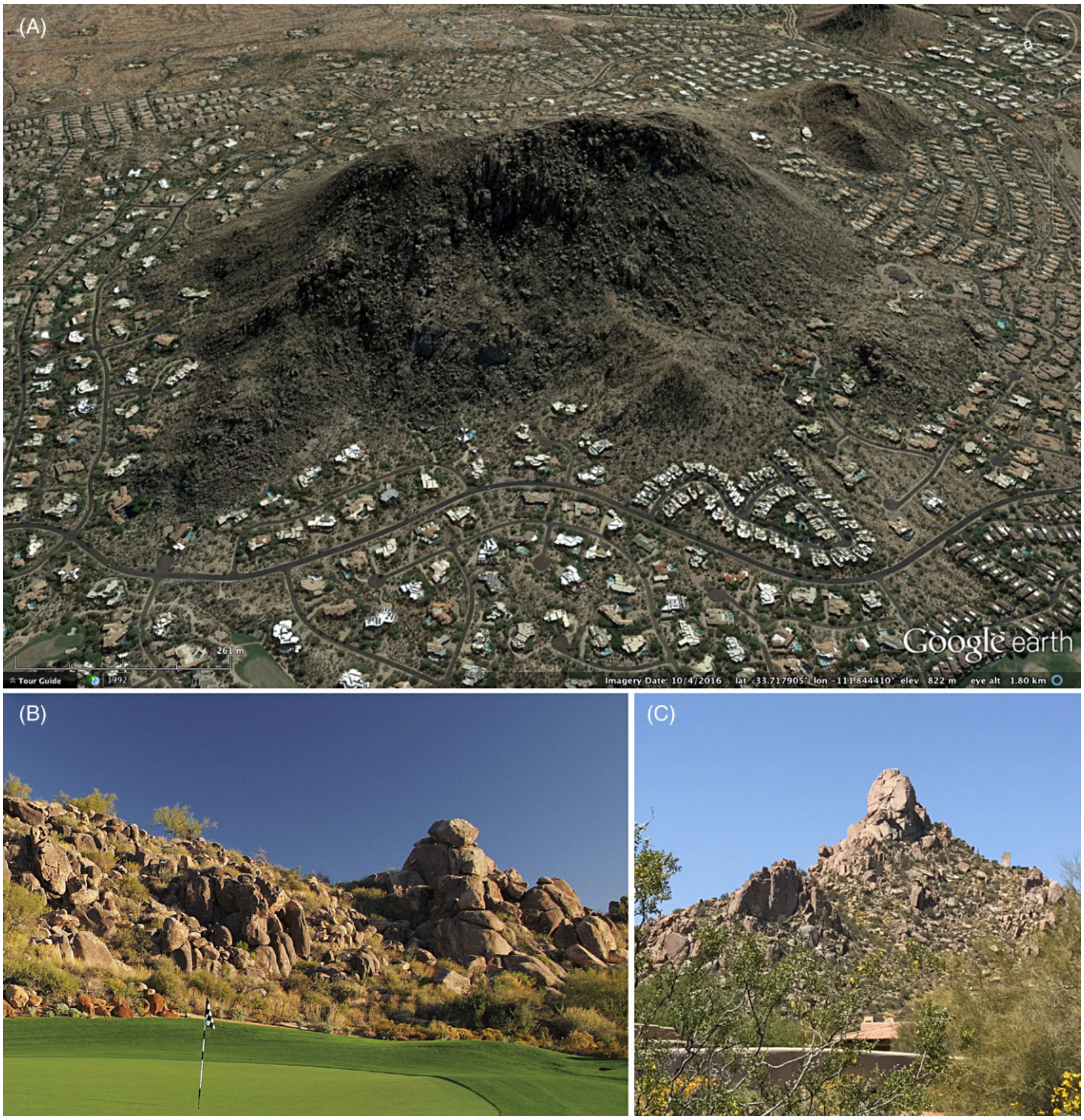

FIGURE 10.4 **Landforms resulting from decay of granite in a desert setting in Scottsdale create an aesthetic setting for the wealthy in metropolitan, Phoenix.** (A) Troon Mountain, a bornhardt, is surrounded by large home and mansions. (B) Golf courses place greens adjacent to spheroidal core stones and tors. (C) Large homes and mansions surround the collapsed bornhardt known as Pinnacle Peak, a kopje. *Source: (A) The image is used following permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html).*

surrounding granitic rocks with high joint-density experience more active mineral decay to grus. Eventually, the existing joints in bornhardts separate, leading to rock slides and collapse into a landform known as a "kopje" (e.g., Fig. 10.4C), similar to those studied in Africa and Australia (Michael et al., 2008).

10.2.1.3 Desert Pavements

Desert pavements consist of a smooth surface with closely packed, interlocking pebbles, cobbles, and sometimes with scattered boulders (Fig. 10.5A). Pavements provide insight into the antiquity of the underlying landform (Seong et al., 2016a), aid in the preservation of ancient artifacts (Adelsberger et al., 2013), and can provide information about environmental change (Dietze et al., 2016) and desert soils (Peterson et al., 1995). Although introductory textbooks often attribute desert pavements to deflation winnowing of fines, the desert pavements in the Phoenix area are not a result of wind erosion. In the case of the entire Sonoran Desert, very little evidence of aeolian abrasion exists (Seong et al., 2016a). For example, desert pavements at South Mountain Preserve, Phoenix, have: coatings of rock varnish that deflation would have abraded away (Fig. 10.5A); vesicular Av soil horizons from the accumulation of dust underneath surface clasts (Fig. 10.5B and C); closely spaced clasts separated by silt and clay surfaces; and no evidence of ventifacts.

The desert pavement in the Phoenix area initiate when floods or debris flows deposit loose and unconsolidated clasts on the surface (Fig. 10.5D). Aeolian fines slowly move into the matrix between the large clasts deposits (Fig. 10.5C) and the size of clasts decreases mostly from dirt-cracking processes (Fig. 10.3). As dust accumulates and clast size decreases, the relief of the original "bar-and-swale" topography gradually reduces (Fig. 10.5E). The keys to stable pavements (e.g., Fig. 10.5A) in the Phoenix area are a combination of: a relatively flat surface; the accumulation of allochthonous dust; a lack of headward retreating swales or gullies (Seong et al., 2016a); and most critically a minimal amount of human activity, as even just one vehicle driving over a pavement surface can do damage (Fig. 10.5F).

10.2.1.4 Biological Soil Crusts

Biological soil crusts (BSCs) consist of assemblages of living organisms on soil or rock surfaces in arid and semiarid areas. Typically composed of cyanobacteria, fungi, lichens, and algae, they cover a wide variety of undisturbed Sonoran Desert soils (Fig. 10.6) and protect desert surfaces from erosional shear stresses imposed by overland flow and strong winds (Allen, 2005, 2010).

When soil is wet, the mucilage of cyanobacteria swell and filaments of cyanobacteria move up toward the soil surface (Belnap et al., 2001). This repeated swelling and frequent movement leaves copious sheath material in the uppermost soil layers that, in turn, maintains soil structure after BSCs are dehydrated and soil particles become loose (Belnap, 2003). Thus, BSCs, and especially filamentous cyanobacteria, adhere to and aggregate with soil particles and their cohesion increases surface stability and inhibits erosion in arid and semiarid lands (Belnap, 2003; Bowker et al., 2008).

Although BSCs are extremely well adapted to the harsh growing conditions in deserts, they can be significantly altered by disturbances, such as grazing, recreational activities (hiking, biking, and off-road driving), and military activities (Belnap and Gillette, 1998) (Fig. 10.6). Faist et al. (2017) examined BSC hydrologic responses to disturbance at different crustal development stages on sandy soils on the Colorado Plateau through a simulated rainfall experiment. They found that trampling well-developed dark cyano-lichen-dominated crusts increased total sediment loss by nearly four times in comparison to intact controls during a 30 min simulated precipitation event, suggesting that well-developed, intact dark BSCs generally decrease runoff and sediment loss and considerably increase aggregate stability (Faist et al., 2017). While BSCs are extremely vulnerable to disturbance, their recovery time can be

FIGURE 10.5 Desert pavement surfaces at South Mountain, Phoenix. (A) Pleistocene desert pavement showing weathered clasts that are closely packed and interlocked, where the sunhat provides scale. (B) Dust accumulation underneath surface clasts seen after removal of the pavement clasts with rock hammer for scale. (C) Vesicular soil horizon termed the Av horizon and the underlying Bk horizon with carbonate-covered clasts, where the Av/Bk boundary is only about 5 cm beneath the pavement. (D) Flood deposits typically maintain a rough bar and swale form; the sunhat provides scale. (E) Over time, the relief of the bar-and-swale topography decreases as swales fill in and bars erode; desert scrub vegetation with a height of 70 cm provides scale. (F) Desert pavement impacted by just one vehicle (*arrow*).

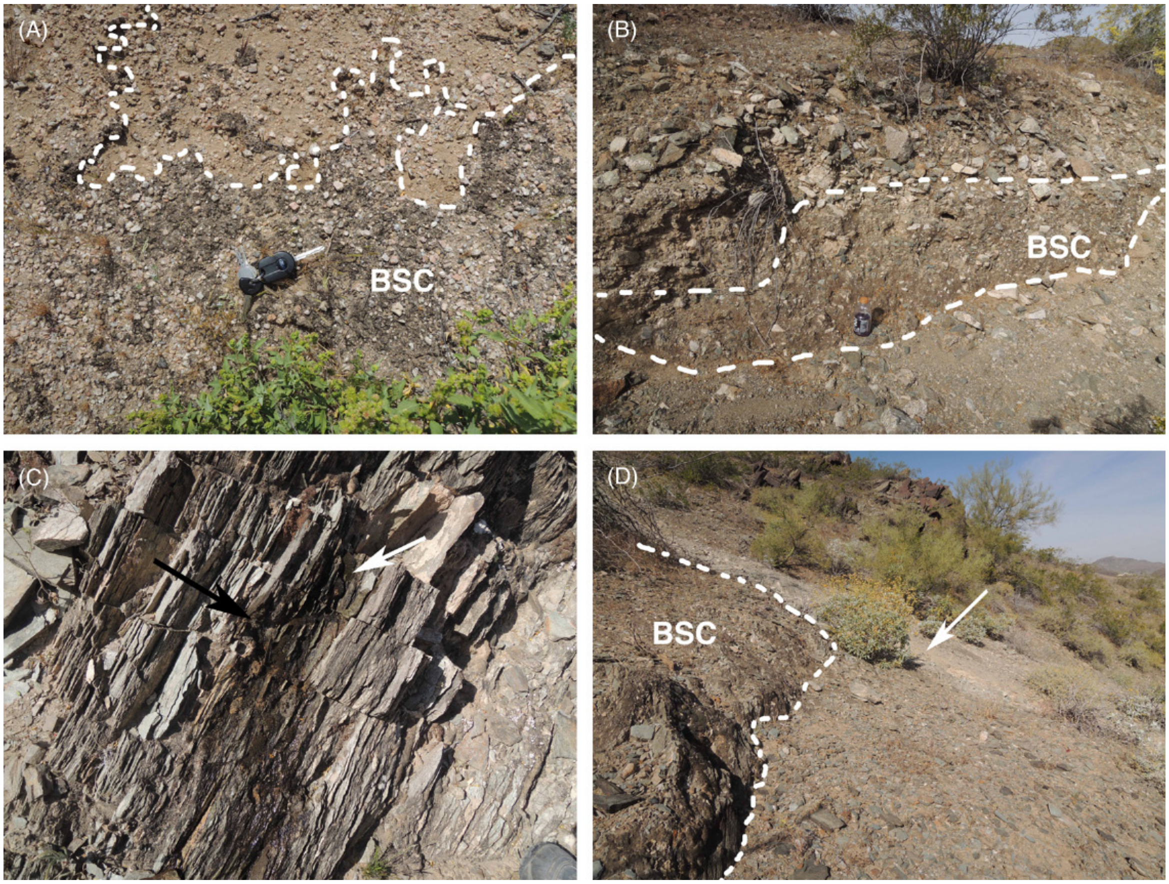

FIGURE 10.6 **Biological crusts on soil and rock surfaces in metropolitan Phoenix.** (A) Biological crusts on a soil surface with car keys for scale. The upper portion of the image was disturbed by the compressive force of cattle grazing, although some recovery has occurred as seen in the lower half of the image (underneath *dashed line*) over the past 12 years since cattle grazing ceased. (B) Biological soil crusts growing on the side of the east-facing side of a desert wash, an aspect that reduces exposure to directly sunlight in the warmest part of the day. (C) Biological soil crusts on a rock surface, where the surface was wetted resulting in a greening up by the algae (*white arrow*); however, BSCs dominated by fungi did not green up (*black arrow*). (D) Biological soil crusts disturbed along a hiking trail, but still evident away from the trail to the left of the *dashed white line*.

relatively slow. No growth of BSCs occurred in the central Namib, for example, over an 8-year period of observation (Viles, 2008).

10.2.1.5 Rock Coatings

A variety of different rock coatings occur throughout the metropolitan Phoenix area, but manganese(Mn)-rich rock varnish darkens the vast majority of exposed rock faces. Fig. 10.7A illustrates the typical appearance of rock varnish. Fig. 10.7C presents an ultrathin section of varnish, revealing the presence of fine micrometer-scale laminations or "microlaminations." These layers form as a result of Holocene and Pleistocene climatic changes (Liu and Broecker, 2007, 2008). Where these layers have been calibrated by independent ages (Liu, 2017), it is possible to assign millennial-scale ages to landforms (Liu and Broecker, 2013).

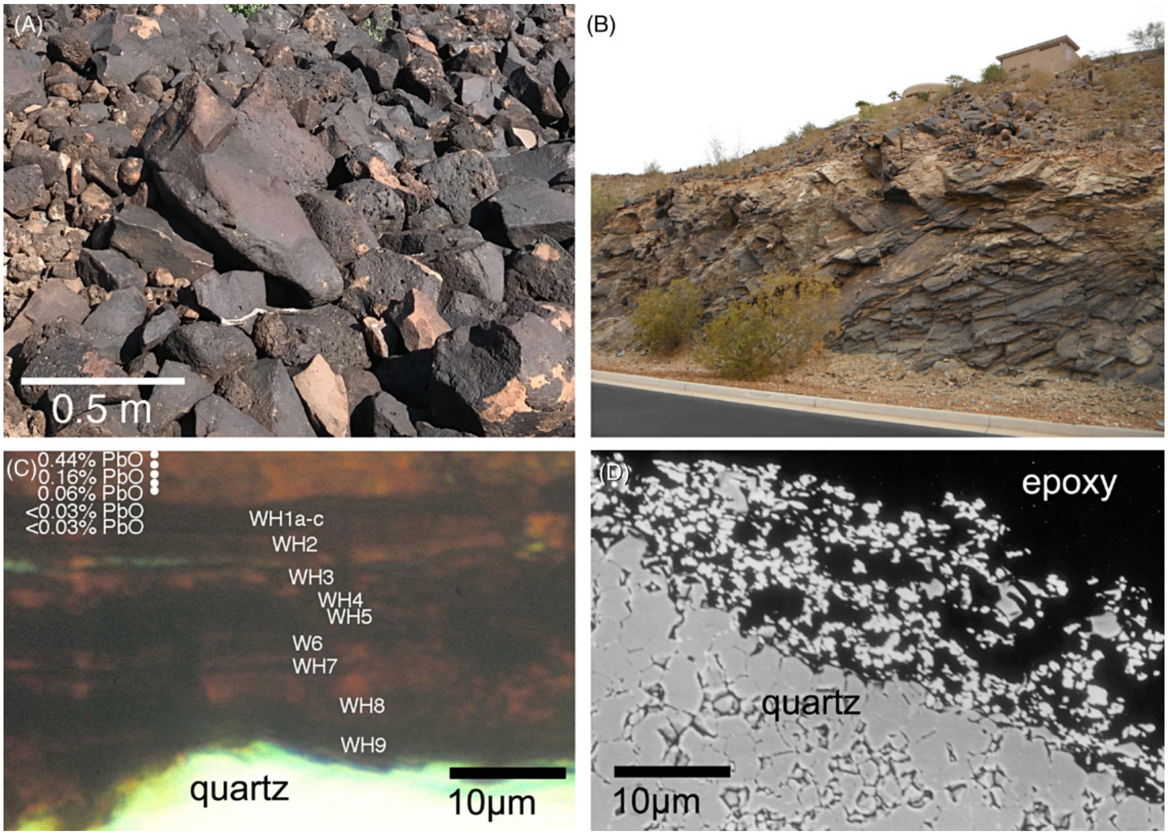

FIGURE 10.7 **Rock varnish as the dominant natural rock coating in metropolitan Phoenix.** (A) Colluvial boulder field at Shaw Butte darkened by rock varnish. The occasional orange Fe film indicates rocks spalled by the dirt cracking process (Fig. 10.3). (B) Urbanization tends to create scars across rock faces, but developers in an affluent Phoenix neighborhood applied "artificial varnish" to minimize the aethestic impact of this road cut. (C) Microlaminations form discrete black, orange, and yellow layers in rock varnish thin sections. (D) Back-scattered electron microscope image of artificial varnish from image B that is experiencing ongoing dissolution, generating a granule-like appearance.

In the case of Fig. 10.7C, a varnish started to form about 8.1 ka, indicated by wet holocene (WH) layer WH9 at the base of the varnish.

Human activity has left a distinct chemical imprint on rock varnishes. The Fe and Mn hydroxides that provide the varnish color scavenges Pb, for example Pb additives used in gasoline in the early part of the 20th century. This Pb accumulates in the surface-most micron of the varnish (Fig. 10.7C), as evidenced by electron microprobe measurements (e.g., 0.44% PbO in Fig. 10.7C). Such "spikes" in Pb abundance are far greater than background levels seen in natural varnish of <0.03% PbO. Although this Anthropocene signal may seem negative at first, representing widespread contamination, the Pb actually provides a useful chronometric marker able to identify purely 20th-century flooding surfaces as well as authentication of rock engravings (Dorn et al., 2012).

The dominance of rock varnish makes it easy to spot anthropogenic disturbances associated with urban construction because the underlying rock is always much lighter in color when disturbed. Some developers in affluent communities decided to try an experimental treatment of artificial varnish (Elvidge and Moore, 1980) to reduce the aesthetic impact of road construction, as seen in the road cut shown in Fig. 10.7B. This artificial varnish is slowly dissolving into granules (Fig. 10.7D). In contrast to natural varnish, artificial varnish has not been binded with clay minerals that, in turn, help cement natural varnish to the underlying rock (Dorn and Oberlander, 1982).

10.2.2 Interplay of Aeolian, Fluvial, and Anthropogenic Processes

The interaction between aeolian and fluvial processes can be an important factor in the shaping of dryland environments (Bullard and Livingstone, 2002). Source-bordering dunes represent a common landform in many dryland environments, such as dunes closely bordering a river (Page et al., 2001). When these fluvial sediments are exposed to the air during a prolonged dry period, winds are more likely to affect sediment transport and wind velocity and particle size are critical factors to entrain sediments.

Two large exoreic river systems cross the Phoenix metropolitan area. The Salt River runs through the center, while the Gila River flows along the southern boundary. A small area of source-bordering dunes and a sand sheet occurs north of the Gila River (Fig. 10.8).

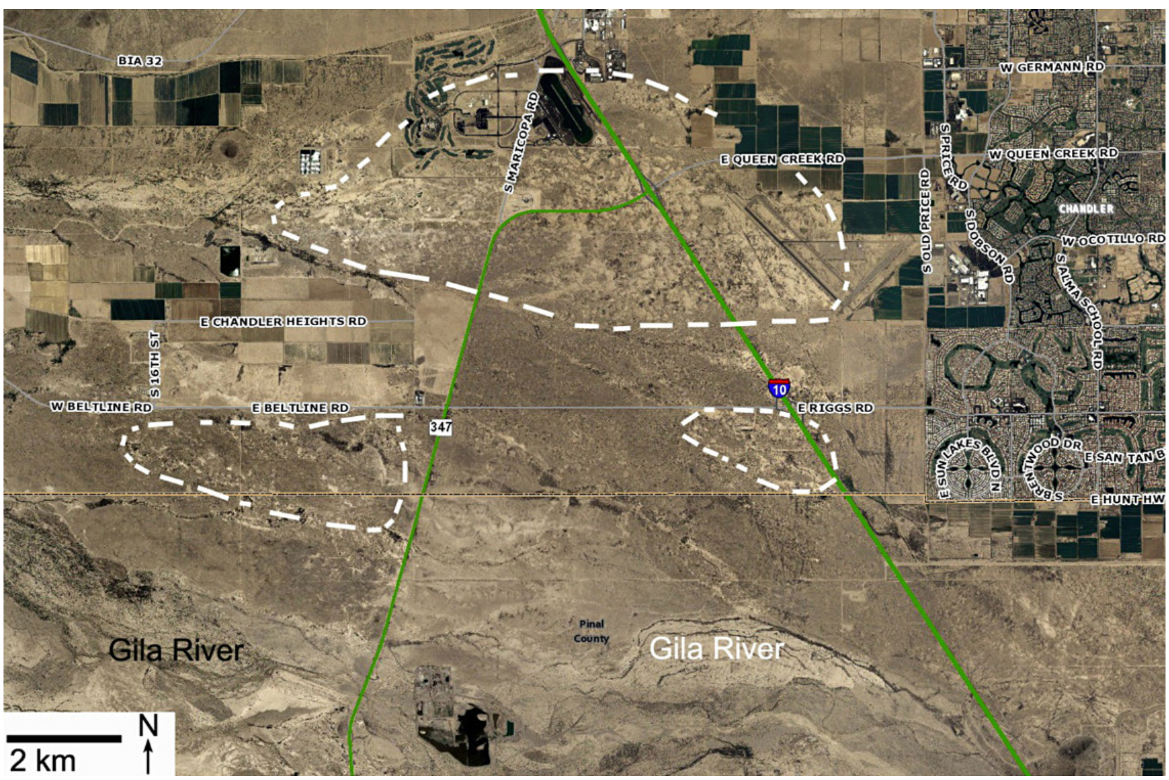

FIGURE 10.8 Source bordering dunes near the Gila River in the southern part of the Phoenix Metropolitan area. Areas denoted by the *dashed lines* locate areas with distinct dune forms. However, the land between these areas is covered by a sand sheet.

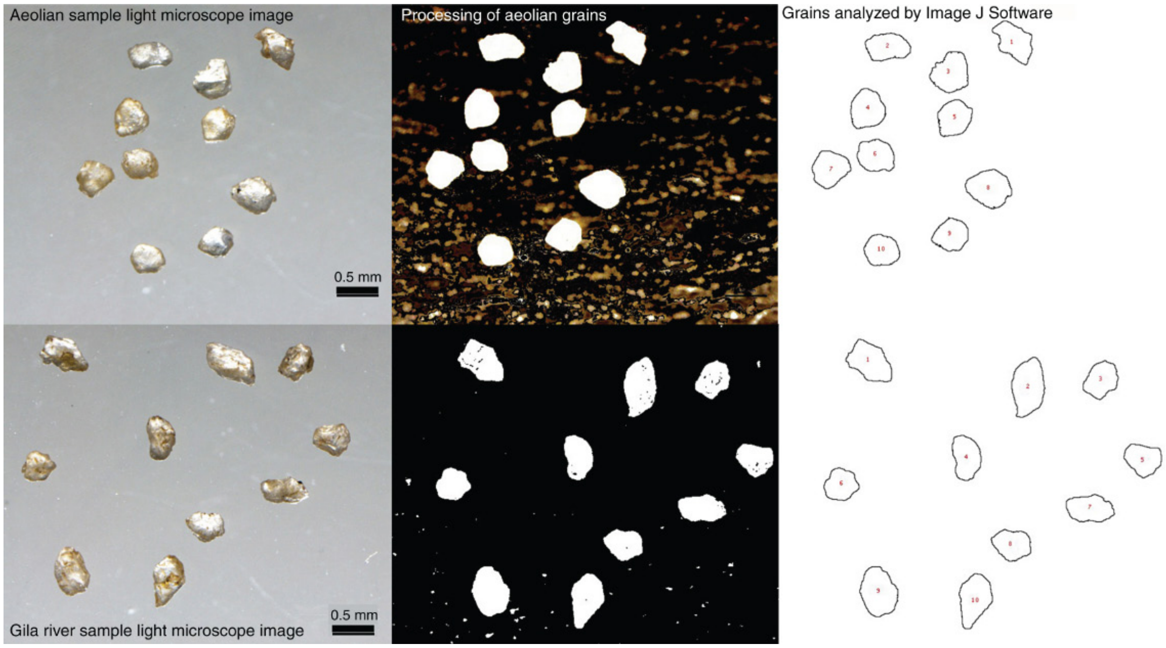

FIGURE 10.9 **Grain size analysis of aeolian and fluvial sediments using the ImageJ software.** The aeolian sample (*upper row*) from source-bordering dunes display more rounding than the fluvial sediments from the Gila River (*lower row*). The grains are first imaged with light microscopy (*left column*), then subject to digital image processing (*middle column*), and the resultant grain perimeter is used by ImageJ software to generate shape parameters. The result of grain shape analysis shows that aeolian sediments have a higher value in roundness (0.78–0.79) and a lower ratio in aspect ratio (1.29–1.30) than fluvial sediment that has 0.70–0.72 in roundness and 1.45–1.50 in aspect ratio.

Using the method developed by Eamer et al. (2017), sediments collected from the Gila River show considerably less rounding than sediments collected from source-bordering dunes (Fig. 10.9).

This area experienced a variety of land uses, including cattle grazing, irrigated agriculture, road construction, and the building of subdivisions. Concomitantly, human activities along the Gila River altered the natural river system, hydrological processes, and, thus, sediment supply to these source-bordering dunes.

Construction of the Coolidge Dam in the upper course of Gila River in 1928 greatly reduced the flood frequency and flood magnitude, leading to a decline in sediment supply. At the same time, an invasive species, Tamarisk, invaded the riparian zone of the Gila River and spread rapidly in the 1900s (Graf, 1988). The presence of Tamarisk affects both aeolian and fluvial processes in terms of reducing the sediments in transport and shear stress on the soil surface. These anthropogenic effects likely decreased sediment transport to the Gila source-bordering dunes. However, extreme weather events, such as the 1993 flood in Phoenix, triggered by El Niño, reactivated the formation of sandbars and changed the channel form to a braided stream pattern along the Gila River due to increased sediment supply. Fig. 10.10 summarizes some of the major controls influencing the potential supply of sediment along the Gila located next to the dunes.

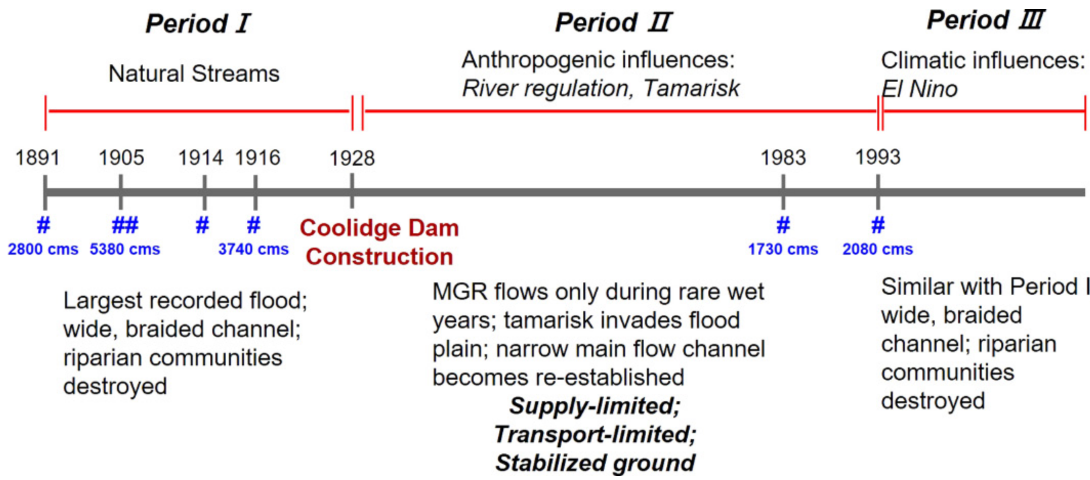

FIGURE 10.10 **Timeline of anthropogenic alteration and large flood events along the Gila River.** *Period I*: Gila River was a natural channel with frequent seasonal flooding. *Period II*: Anthropogenic activities altered the natural channel system of Gila River, largely reducing sediment supply for both aeolian and fluvial transport as well as flood frequency. *Period III*: Extreme climatic events caused large floods along the Gila River reactivated aeolian and fluvial-transport processes due to the increased sediment availability.

Extensive areas of the cities of Chandler, Gilbert, Mesa, and Tempe in the metropolitan area are covered by several meters of fine sandy material. This material could have been derived in part by aeolian transport from the Gila River. In addition, there are lenses of river-transported gravels and cobbles derived from bordering mountains. Thus, it is likely that aeolian and fluvial processes resulted in a mixture of a sand sheet intercalating with low-energy rivers. Fig. 10.11 illustrates an anthropogenic excavation into this mixed, interdigitated aeolian and fluvial deposit.

10.2.3 Mass Wasting

Talus from rockfalls and rockslides covers steep slopes of desert mountain ranges throughout the southwestern USA (Melton, 1965; Parsons et al., 2009). Urban expansion in arid regions globally (Cooke et al., 1982) continues to thrust infrastructure at the base of steep desert slopes. This is certainly the case in the Phoenix area (Dorn, 2014; Harris and Pearthree, 2002), where the wealthy build homes right on the margins of mountain preserves (Ewan et al., 2004) and often beneath steep bare rockfaces (Fig. 10.12). Chronometric studies of rockfall in the Phoenix area reveal that rockfalls occurred throughout the Holocene (Dorn, 2014) and historically in the Anthropocene.

Debris flows are one of the most hazardous landslide types in any region with steep terrain and precipitation, including the Phoenix area (Dorn, 2012, 2016). Debris flows occur when slopes fail to maintain the equilibrium between gravitational drivings and frictional resisting forces (Iverson, 2005). Thus, they typically occur on steep-slope areas between 20 and 45° after prolonged or particularly intense wetting events (Jakob and Hungr, 2005); in the case of the Phoenix area, from thunderstorms, soaking hurricane moisture, or a series of winter frontal storms (Dorn, 2016).

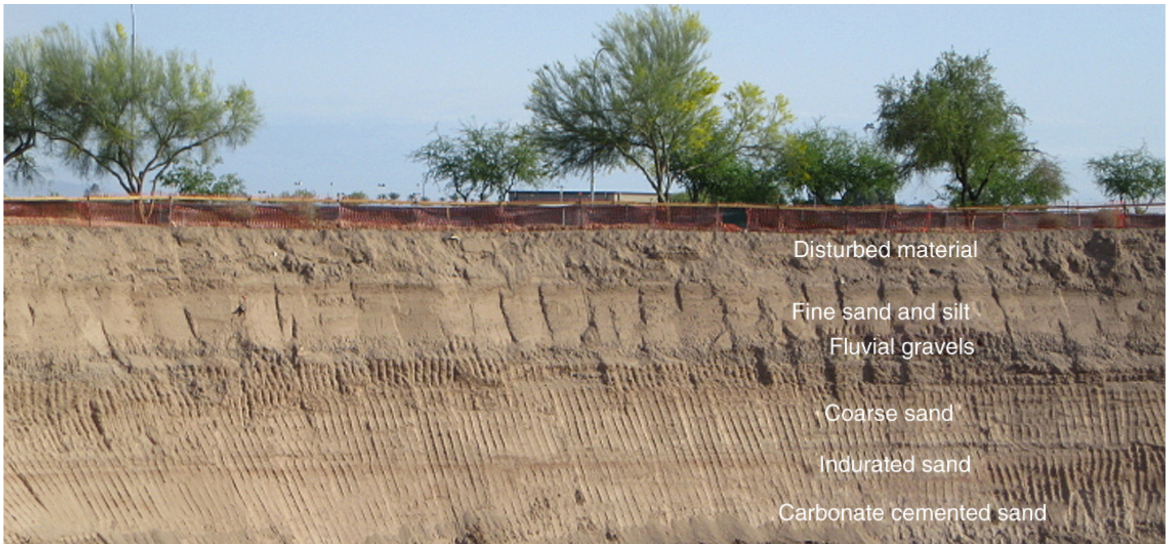

FIGURE 10.11 **An excavation exposed the mixed fluvial and aeolian deposit located between the Salt and the Gila Rivers in metropolitan Phoenix.** Some sediments are clearly fluvial gravels, while sandy units show evidence of both fluvial and aeolian transport. Carbonate cementation could be related to groundwater processes or pedogenic processes. 4-m tall Paloverde trees provide scale. The uppermost 1.5 m consists of rock and sand from construction activities.

Debris flows have three major zones, including initiation, transportation, and deposition (Fig. 10.13) (Jakob and Hungr, 2005), and geomorphic features can be identified in each zone. Distinct head scarps indicate the initiation zone, where slope failures start. Once initiated, chutes develop along the debris-flow channel, and debris-flow materials are transported down slope. Finally, debris flows produce levees and alluvial fans at the mouths of drainages (Fig. 10.13A and B) (Webb et al., 2008; Youberg et al., 2008). In the case of most debris-flow contexts in Phoenix, the chutes are only a few hundred meters long and the alluvial fans that result exist only at the base of the slopes, as illustrated in Fig. 10.13.

Rockslides are another type of mass wasting that involves the displacement of rock materials along a sliding plane, such as a bedding plane, and the interface between two different rock types. Granitic rocks experience sheeting and produce pressure-release shells once the overlying materials have been removed (Bahat et al., 1999). The Phoenix neighborhood of Awhatukee illustrates three different types of mass-wasting events associated with pressure release shells: debris flows (Fig. 10.14B), rockfalls (Fig. 10.14C), and rockslides (Fig. 10.14D). What may be surprising is that the homeowners at the base of these steeply dipping joint faces have little to no understanding of the potential hazard just meters from their homes.

10.2.4 Pedimentation

The Phoenix metropolitan area hosts iconic pediments with a variety of rock types that makes this area the rival of other well-known pediment sites on Earth (Fig. 10.15). Pediments with the classic sharp piedmont angle exist on Forest Service and city preserve lands, allowing

FIGURE 10.12 Historic rockfalls place wealthy homes in potential danger in such areas as Camelback Mountain (A) and the Phoenix Mountains (B).

for study of the entire inselberg-pediment landscape (Fig. 10.15A, B, D, and H). The largest expanse of pediments, however, rests under urban sprawl (Fig. 10.15C, F, and G).

The pediment literature maintains an extensive bias toward granitic study sites (Dohrenwend and Parsons, 2009), including central Arizona (Kesel, 1977; Pelletier, 2010). However, the Phoenix area contains pediments in four broad rock types (Larson et al., 2016): granitic (Fig. 10.15A, B, and D); foliated metamorphic (Fig. 10.15C, G, and H); sedimentary

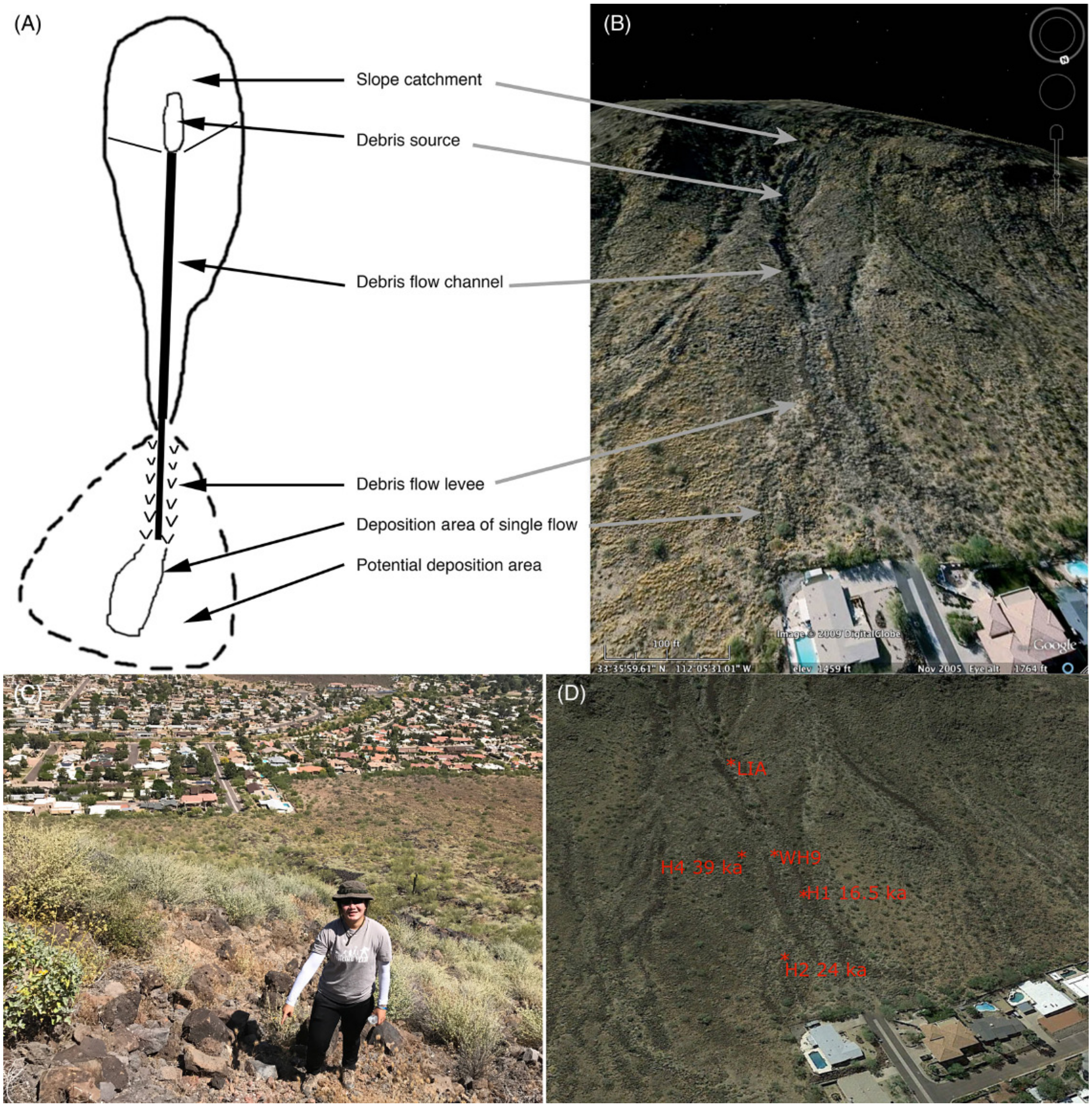

FIGURE 10.13 Shaw Butte in the Phoenix Mountains illustrates how debris flows interface with urbanization. (A) and (B) illustrate the debris-flow system, where small catchments generate debris flows that move down chutes a few hundred meters long, resulting in debris-flow deposition near the mountain front. (C) illustrates the source region of the most recent Little Ice Age flow that occurred about 0.65 ka. (D) identifies debris-flow deposits about 8.1, 16.5, 24, and 39 ka. However, an unknown number of other debris flows occurred, with evidence destroyed by subsequent events. *Source: The images in B and D are used following permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html).*

FIGURE 10.14 (A) is from the perspective of looking at the mountain slope from the resident's back fence, where (B) debris flow levees, (C) talus from rockfalls, and (D) a rockslide all represent hazards above a suburban neighborhood. Note the massive rock in (D) that is situated on the pressure-release joint of granitic surface with little to no support to inhibit the next mass-wasting event.

breccia with extensive sandy facies (Fig. 10.15E and F); and ignimbrite. Given this mixed lithology, explanations of the pediment form requiring differential decay of granitic rocks and fossilized landscapes (Oberlander, 1989) do not work, since similar forms exist side-by-side in rock types other than granite. Furthermore, given the central Arizona evidence that pediment forms are able to adjust to base-level change in the timeframe of the last glacial cycle (Larson et al., 2016), also removes the need for complicated explanations of form requiring two-stage etching (Twidale, 2002).

Our view of pedimentation as a process in the Phoenix area returns to early German geomorphological thinking (Penck, 1924); G.K. Gilbert's classic observations (Gilbert, 1877); and more modern process-geomorphic interpretations (Applegarth, 2004; Larson et al., 2016; Parsons and Abrahams, 1984). Pediments function as transport surfaces (conveyor belts) of materials detached and eroded from small mountain masses. Pediments form where drainage

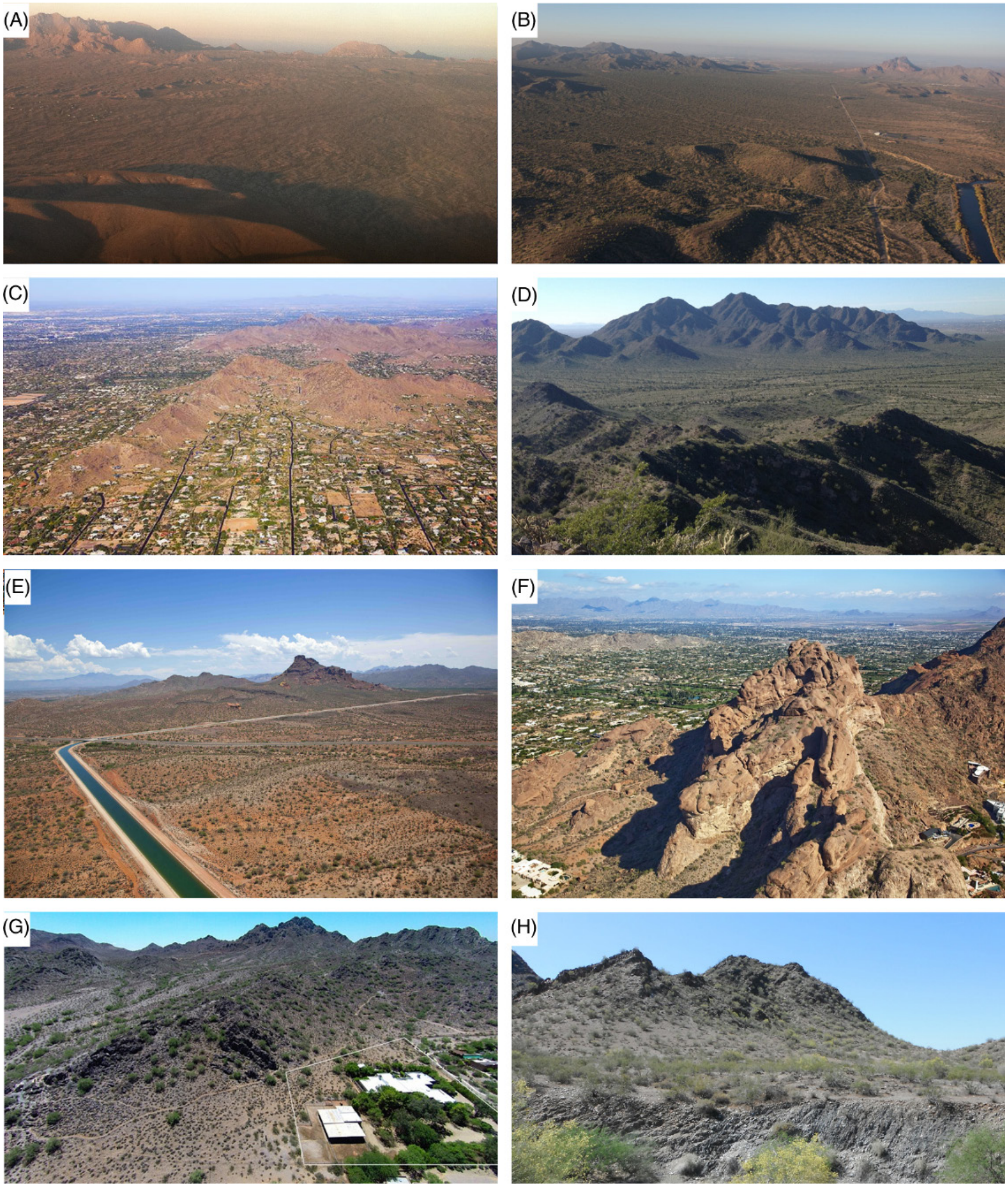

FIGURE 10.15 **Pediment-inselberg landscapes of metropolitan Pheonix, illustrating planar pediments in front of small inselberg ranges.** (A) granitic eastern McDowell Mountains; (B) granitic northern Usery Mountains; (C) foliated metamorphic Mummy Mountain; (D) granitic San Tan Mountains; (E) breccia Red Mountain; (F) breccia Camelback Mountains; (G) massive metamorphic North Mountain; and (H) foliated metamorphic Phoenix Mountains.

areas are too small to develop alluvial fans. The classic piedmont angle, which is seen as a fairly dramatic slope break, results from the greater resistance to detachment and transport of larger slope colluvial particles and bedrock that leads to the generation of steeper slopes. The slopes of once-graded pediments led to closed basins throughout the late Miocene and Pliocene, but pediments have been experiencing ongoing adjustment to fluctuating base level throughout the Quaternary (Larson et al., 2014)

10.3 DESERT GEOMORPHIC HAZARDS

10.3.1 Alluvial Fan Flooding

The basic ephemeral channel morphologies of the Sonoran Desert (Sutfin et al., 2014) include bedrock channels in the upper interior of the drainage that transitions to bedrock mixed with alluvium and ultimately to incised alluvium at an embayment that merges into an alluvial-fan piedmont. For much of the Sonoran Desert, including Phoenix, the alluvial-fan piedmont is incised. The risk for flooding only comes where the channel emerges from the incised area and is then able to experience an avulsion (Fuller, 2012). Such alluvial-fan avulsions only occur below the hydrological apex and not on older abandoned alluvial-fan surfaces.

The Federal Emergency Management Agency (FEMA) uses a procedure for delineating flood-hazard zones on alluvial fans, with fiscal implications for those building on surfaces so delineated on flood insurance-rate maps based on the FEMA approach. Put simplistically, FEMA treats as potentially hazardous all surfaces beneath the topographic apex of a fan. However, vast tracks of land in the 100-year flood-hazard zone are not truly flood prone if they exist above the hydrological apex. Such a condition occurs when there is a “fan-head trench” that delivers water and sediment in a naturally incised water conduit toward the toe of the fan form. Prior research indicates that the FEMA approach simply does not work in places like Laughlin, Nevada (House, 2005); Tucson, Arizona (Pearthree et al., 1992); and certainly not in the Phoenix area (Fuller, 1990). Fig. 10.16 illustrates the offset between the FEMA procedure and reality in the community of Scottsdale, Arizona.

10.3.2 Street Flooding in Planned and Unplanned Housing Developments

Street flooding occurs throughout the Phoenix metropolitan area, typically during the summer monsoon season, when short, but intense, downbursts result in localized overland flow. The local Maricopa County Flood Control District receives property tax funding to route water efficiently through the metropolitan area, working with local municipalities (Fig. 10.17). The county and cities can take different cost-benefit strategies to dealing with street flash flooding. Over-engineering has often been done by the county. However, local communities have made other choices at times.

The homes, infrastructure, and retail space of the Phoenix suburb of Fountain Hills rests on an eroding alluvial fan landform known as a “ballena” (Fig. 10.18). However, the roads cross a series of incised ephemeral washes that experience frequent flooding (Rhoads, 1986). The management challenge rests in the cost-benefit trade-off of engineering for decadal events,

FIGURE 10.16 Development burgeoned on alluvial-fan surfaces during the 1990s, as shown in a comparison of 1991 (A) and 1995 (B) aerial photographs of the southern McDowell Mountains, Scottsdale. In the 1991 image, *dots* delineate the presence of entrenched channels transporting water and sediment almost 8 km downstream from this fan. Thus, with the hydrological apex located at distance from the topographic apex of the alluvial fan, all of the development is safe from fan-related flooding.

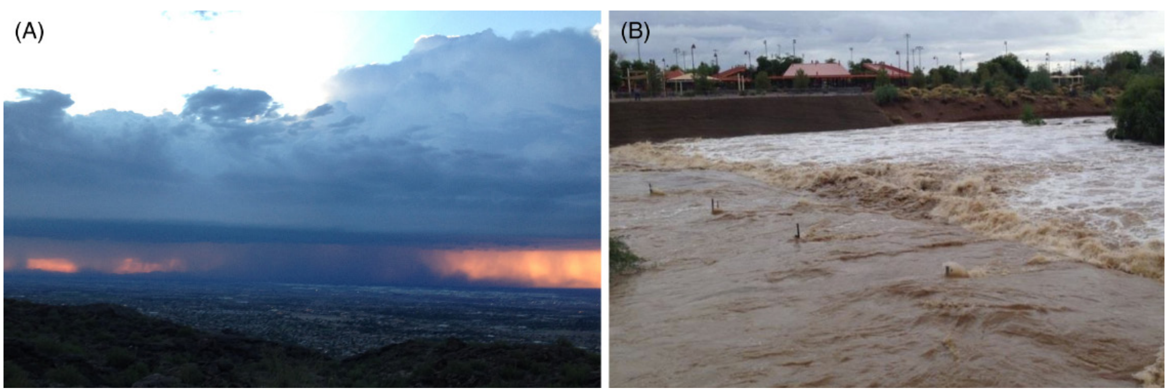

FIGURE 10.17 Monsoon downburst taking place over the western portion of metropolitan Phoenix (A) and corresponding localized flooding being routed through flood-control structures (B).

and then let century or millennial-scale flash flooding require infrastructure replacement. This leads to ongoing construction at problem locations, where initial engineering structures have repeatedly failed.

Much of Phoenix has been built on pediments with low slopes (Fig. 10.19). The engineering associated with this development ranges considerably in terms of the investment to deal

FIGURE 10.18 **Fountain Hills is a community built on a ballena, or eroding alluvial fan. Although structures are safe because homes and businesses are placed on ballena tops and side slopes, roads must be engineered to survive occasional flooding in the washes between the ridges.**

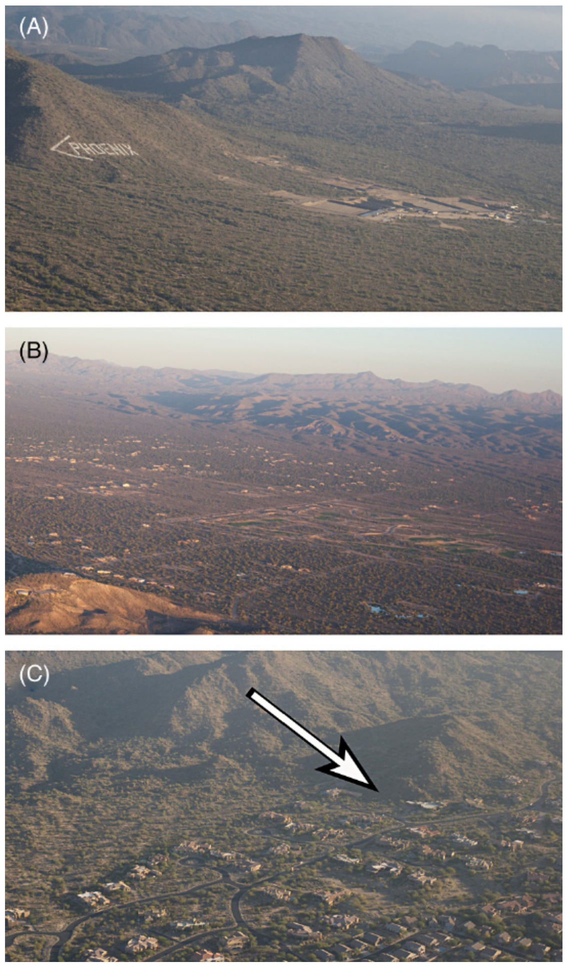

FIGURE 10.19 **Development on pediments takes different strategies in dealing with ephemeral flooding.** (A) A gun club simply built large levees to divert flow into the surrounding desert. (B) A "wildcat" development called Rio Verde continues to experience localized flooding, since little or no effort focuses on water routing during home or road construction. (C) Affluent subdivisions do consider flash flooding issues and route water into natural or human-enhanced washes. The arrow identifies the classic sudden break in slope between inselberg and pediment.

with ephemeral flooding. In Fig. 10.19A, a gun club has built simple berms to deflect flooding around the complex. In contrast, Fig. 10.19B displays a wildcat community known as "Rio Verde." This development is almost entirely unplanned with respect to dealing with runoff. An individual purchasing a plot of land will build, quite often, without any concern for the flooding issues caused by upstream neighbors or that they may cause for downstream property owners. More wealthy communities, such as the exclusive Las Sendas neighborhood of Mesa (Fig. 10.19C), include structures to deal with the routing of water.

The largest river running through metropolitan Phoenix has ceased to pose a flooding hazard. Throughout the 20th century, the Salt River flooded repeatedly, causing considerable losses to property and sometimes lives (Gober, 2005). However, the last time that the Salt River experienced destruction associated with flooding took place in 1993 during a major El Nino Southern Oscillation (ENSO) event (Fig. 10.20C) that corresponded with construction at Roosevelt Dam (Fig. 10.20A), requiring the release of water from the reservoir behind. The combination of a

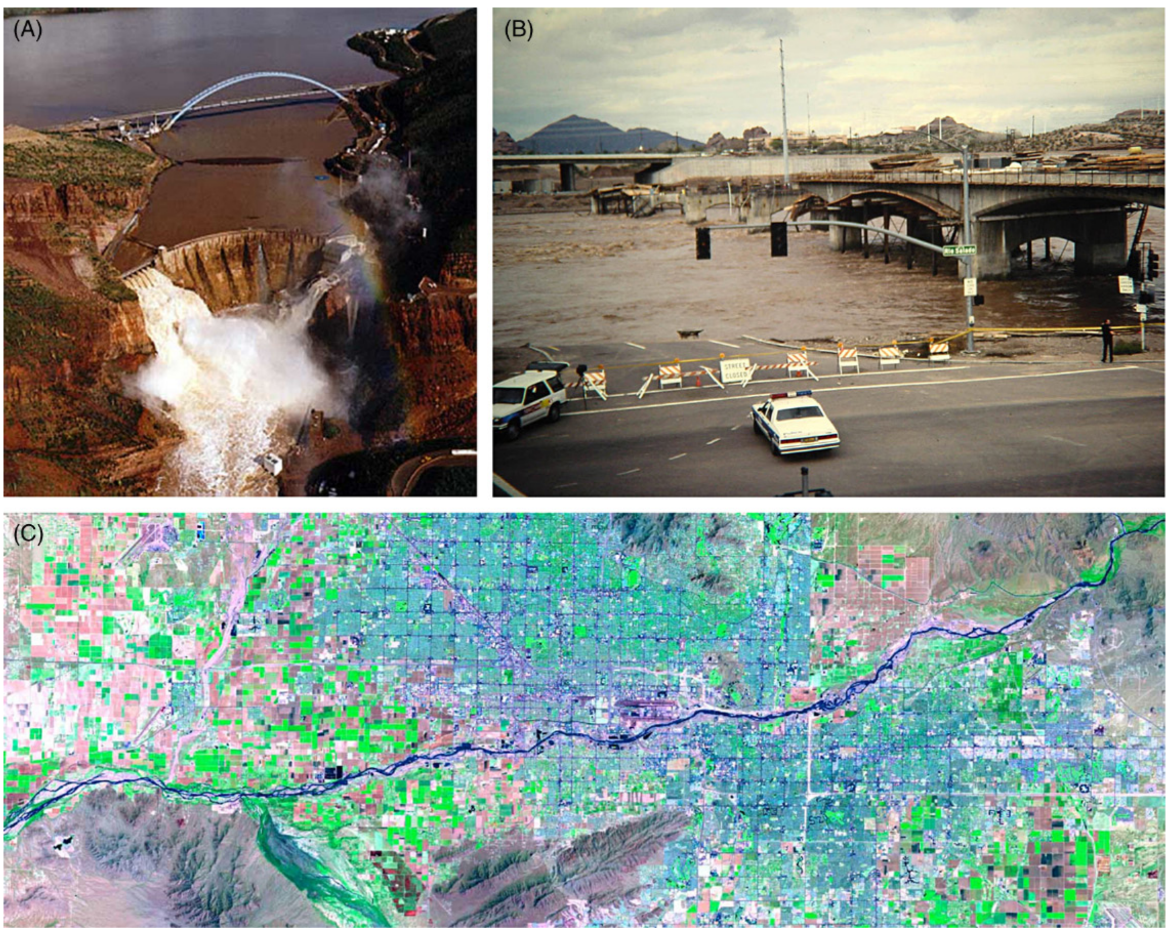

FIGURE 10.20 During the winter of 1993, a major ENSO event led to (A) the release of water from the reservoir behind the Roosevelt Dam. The released water destroyed the bridge at Mill Avenue in Tempe (B) as well as other infrastructure along the course of the river through metropolitan Phoenix. *Source: (A) and (C) are copyright free and made available courtesy of the Bureau of Reclamation (A) and NASA (B).*

very wet winter and a lowered dam level destroyed bridges and a lot of other infrastructure (Fig. 10.20B). However, since the Roosevelt Dam's 1993 construction resulted in increased reservoir capacity, flooding has not been an issue since along this major drainage.

10.3.3 Debris Flows

The Phoenix urban area has expanded out into the surrounded mountain fronts, where debris flows take place. In an initial study of the hazard to homes posed by debris flows, Dorn (2012) found that at least 89 houses are located along the pathway of former debris flows or above the debris flow chutes of the Gila Range and the Ma Ha Tuak Range of South Mountain, Camelback Mountain, Mummy Mountain, and Shaw Butte areas alone (Fig. 10.13).

Debris flows were not generally viewed as a hazard in the Sonoran Desert, until a major debris flow event occurred outside of Tucson (Youberg et al., 2008). Despite evidence to the contrary, those geoscientists living in and around Phoenix generally considered debris flows "acts of God," or extraordinarily rare geological events not worthy of study. This changed after an intense summer thunderstorm on August 12, 2014, and a hurricane that occurred on September 8, 2014, led to short and intensive precipitation events in metropolitan Phoenix, which triggered the occurrence of dozens of debris flows in one mountain range of Phoenix alone (Fig. 10.21) (Dorn, 2016).

10.3.4 Haboobs and Dust Storms

Dust and summer dust storms are part of the urban geomorphic and climate system (Brazel, 1989; Marcus and Brazel, 1992; Péwé et al., 1981). During the spring, strong dry cold fronts deflate dust from agricultural fields and abandon urban lots, producing a substantial dust hazard. During the months of July, August, and September, the Mexican monsoon's northern boundary impacts the Phoenix area and produces haboobs (Idso et al., 1972), like the one seen in Fig. 10.22, which are associated with the leading edge of cold outflow from

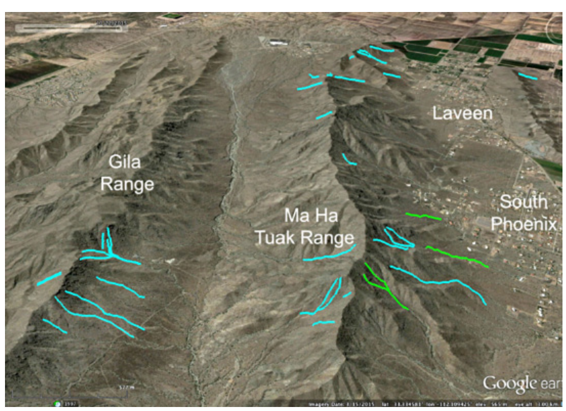

FIGURE 10.21 **West-looking view of the debris-flow pathways triggered by the August 12th hurricane thunderstorm (blue) and September 8th summer monsoon event (green) at South Mountain, Phoenix in 2014 (Dorn, 2016).** *Source: The base image is used following permission guidelines for Google Earth (http://www.google.com/permissions/geoguidelines.html).*

FIGURE 10.22 **A km-high, nearly 100-km wide haboob approaches Phoenix from the south at sunset.**

convective clouds. Although this is a natural phenomenon, anthropogenic activities that led to the exposure of bare ground (e.g., exposed house pads, agricultural fields, desertification) all contribute to the available surface area for dust deflation (Eagar et al., 2017).

Dust poses a regular urban hazard in terms of driving, where visibility decreases to the point where a driver is unable to see more than a few meters ahead (Baddock et al., 2013; Hyeres and Marcus, 1981). Desert dust is also associated with a number of human health issues (Goudie, 2014). Valley fever, for example, is produced by the fungus Coccidiodes that lives in soil and dust in the southwestern USA, where the Centers for Disease Control and Prevention indicated Arizona had more than 5000 reported cases each year between 2009 and 2015 (https://www.cdc.gov/fungal/diseases/coccidioidomycosis/statistics.html).

10.4 SUMMARY PERSPECTIVE ON HUMAN INFLUENCES ON THE ARID GEOMORPHIC SYSTEM IN THE URBANIZING SONORAN DESERT

From a geomorphic perspective, the Anthropocene, or the proposed new geological epoch when humans have had an overwhelming effect on the Earth system (Waters et al., 2016), requires both empirical evidence and an understanding of exactly how humans alter geomorphic processes. Accordingly, the British Society for Geomorphology maintains a Fixed Term Working Group to advise how geomorphologists should engage in scholarly analysis concerning the Anthropocene as a concept. Practical aspects include a relative magnitude problem, a boundary problem, and a spatial problem associated with "anthropogenic geomorphology" (Brown et al., 2017).

In the context of urban geomorphology (Thornbush, 2015), where human impacts result in enhanced disturbance and increased vulnerability to erosion, an arid city poses very different considerations than urban centers in wetter regions. Urban geomorphic processes in a setting like the Sonoran Desert are potentially altered by a myriad of anthropogenic influences, including: invasive species turning an ecoregion that did not naturally experience massive wildfires into an annual hazard due to invasive annual grass species; altering the armoring effects of soil crusting by widespread destruction of BSCs by periods of cattle grazing; periods of road building and home construction; and other influences, such as off-road vehicles.

An individual walking on desert landforms, before massive land-use change associated with cattle grazing and urban expansion, likely would have experienced very different surface conditions than found by the average hiker today. Extensive areas once hosted desert pavements, BSCs (Allen, 2005, 2010), and interlocking colluvium on steeper slopes that provided a net-armoring effect (Bowker et al., 2008; Granger et al., 2001; Seong et al., 2016a). Today, only patches of such armored surfaces remain, providing glimpses into the original land surfaces.

According to Brown et al. (2017), "it is clear that the relevance of the Anthropocene concept varies substantially between different branches of geomorphology", (p. 71). While Brown et al. (2017) did not consider rocky desert landscapes, such as the Phoenix metropolitan area, the basic conclusion that "the less obvious effects of humans on the geomorphic systems warrant increased research", (p. 85) certainly applies to the Phoenix metropolitan area and the surrounding Sonoran Desert. Developing a better understanding of the role of human-influenced processes at different scales will be needed to better diagnose the role of human impacts in an arid geomorphic system.

References

Abrahams, A.D., Parsons, A.J., Hirsch, P.J., 1985. Hillslope gradient-particle size relations: evidence of the formation of debris slopes by hydraulic processes in the Mojave Desert. J. Geol. 93 (3), 347–357.

Adelsberger, K.A., Smith, J.R., McPherron, S.P., Dibble, H.L., Olszewski, D.I., Schurmans, U.A., Chiotti, L., 2013. Desert pavement disturbance and artifact taphonomy: a case study from the Eastern Libyan Plateau Egypt. Geoarchaeol 28 (2), 112–130.

Allen, C., Swetnam, T., Betancourt, J., 1998. Landscape changes in the southwestern United States: techniques, long-term data sets, and trends. Sisk, T.D. (Ed.), Perspectives on the Land-Use History of North America: A Context for Understanding Our Changing Environment, 104, U.S. Geological Survey, Fort Collins, CO, USA.

Allen, C.D., 2005. Micrometeorology of a smooth and rugose biological soil crust near Coon Bluff Arizona. J. Ariz.-Nev. Acad. Sci. 38 (1), 21–28.

Allen, C.D., 2010. Biogeomorphology and biological soil crusts: a symbiotic research relationship. Geomorphologie 16 (4), 347–358.

Applegarth, M.T., 2004. Assessing the influence of mountain slope morphology on pediment form South-Central Arizona. Phys. Geogr. 25 (3), 225–236.

Baddock, M.C., Strong, C.L., Murray, P.S., McTainsh, G.H., 2013. Aeolian dust as a transport hazard. Atmospheric Environ. 71, 7–14.

Bahat, D., Grossenbacher, K., Karasaki, K., 1999. Mechanism of exfoliation joint formation in granitic rocks, Yosemite National Park. J. Struct. Geol. 21 (1), 85–96.

Belnap, J., 2003. The world at your feet: desert biological soil crusts. Front. Ecol. Environ. 1 (4), 81–189.

Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. J. Arid. Environ. 39 (2), 133–142.

Belnap, J., Büdel, B., Lange, O.L., 2001. Biological soil crusts: characteristics and distribution. Ecol. Stud. 150, 3–31.

Bowker, M.A., Belnap, J., Chaudhary, V.B., Johnson, N.C., 2008. Revisiting classic water erosion models in drylands: the strong impact of biological soil crusts. Soil Biol. Biochem. 40 (9), 2309–2316.

Brazel, A.J., 1989. Dust and Climate in the American Southwest. Kluwer Academic Publishers, Dordrecht.

Brown, A.G., Tooth, S., Bullard, J.E., Thomas, D.S., Chiverrell, R.C., Plater, A.J., Murton, J., Thorndycraft, V.R., Tarolli, P., Rose, J., Wainwright, J., 2017. The geomorphology of the Anthropocene: emergence, status and implications. Earth Surf. Process. Land. 42 (1), 71–90.

Bullard, J.E., Livingstone, I., 2002. Interactions between aeolian and fluvial systems in dryland environments. Area 34 (1), 8015.

Coney, P.J., Harms, T.A., 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression. Geology 12 (9), 550–554.
Cooke, R.U., Brunsden, D., Doornkamp, J.C., Jones, D., 1982. Urban Geomorphology in Drylands. Oxford University Press, Oxford.
Dietze, M., Dietze, E., Lomax, J., Fuchs, M., Kleber, A., Wells, S.G., 2016. Environmental history recorded in aeolian deposits under stone pavements, Mojave Desert, USA. Quat. Res. 85 (1), 4–16.
Dohrenwend, J.C., Parsons, A.J., 2009. Pediments in arid environments. In: Parsons, A.J., Abrahams, A.D. (Eds.), Geomorphology of Desert Environments. Springer, New York, pp. 377–411.
Dorn, R.I., 2011. Revisiting dirt cracking as a physical weathering process in warm deserts. Geomorphology 135 (1), 129–142.
Dorn, R.I., 2012. Do debris flows pose a hazard to mountain-front property in metropolitan Phoenix Arizona? Prof. Geogr. 64 (2), 197–210.
Dorn, R.I., 2014. Chronology of rock falls and slides in a desert mountain range: case study from the Sonoran Desert in south-central Arizona. Geomorphology 223, 81–89.
Dorn, R.I., 2016. Identification of debris-flow hazards in warm deserts through analyzing past occurrences: case study in South Mountain, Sonoran Desert, USA. Geomorphology 273, 269–279.
Dorn, R.I., Oberlander, T.M., 1982. Rock varnish. Prog. Phys. Geogr. 6 (3), 317–367.
Dorn, R.I., Gordon, M., Pagán, E.O., Bostwick, T.W., King, M., Ostapuk, P., 2012. Assessing early Spanish explorer routes through authentication of rock inscriptions. Prof. Geogr. 64 (3), 415–429.
Eagar, J.D., Herckes, P., Hartnett, H.E., 2017. The characterization of haboobs and the deposition of dust in Tempe, AZ from 2005 to 2014. Aeolian Res. 24, 81–91.
Eamer, J.B.R., Shugar, D., Walker, I.J., Lian, O., Neudorf, C., 2017. Distinguishing depositional setting for sandy deposits in coastal landscapes using grain shape. J. Sediment. Res. 87, 1–11.
Elvidge, C.D., Moore, C.B., 1980. Restoration of petroglyphs with artificial desert varnish. Stud. Conserv. 25 (3), 108–117.
Ewan, J., Ewan, R.F., Burke, J., 2004. Building ecology into the planning continuum: case study of desert land preservation in Phoenix Arizona (USA). Landsc. Urban Plan. 68 (1), 53–75.
Faist, A.M., Herrick, J.E., Belnap, J., Van Zee, J.W., Barger, N.N., 2017. Biological soil crust and disturbance controls on surface hydrology in a semi-arid ecosystem. Ecosphere 8 (3), e01691.10.1002/ecs2.1691.
Fuller, J.E., 1990. Misapplication of the FEMA alluvial fan model: a case history. In: French, R.H. (Ed.), Hydraulics/Hydrology of Arid Lands (H^2AL). American Society Civil Engineers, New York, pp. 367–372.
Fuller, J.E., 2012. Evaluation of avulsion potential on active alluvial fans in central and western Arizona. Arizona Geological Survey Contributed Report CR-12-D, 1–88.
Gilbert, G.K., 1877. Geology of the Henry Mountains. Geological and Geographical Survey, Washington, DC, U.S.
Gober, P., 2005. Metropolitan Phoenix: Place Making and Community Building in the Desert. University of Pennsylvania Press, Philadelphia.
Goudie, A.S., 2014. Desert dust and human health disorders. Environ. Int. 63, 101–113.
Graf, W.L., 1988. Fluvial Processes in Dryland Rivers. Springer-Verlag.
Granger, D.E., Riebe, C.S., Kirchner, J.W., Finkel, R.C., 2001. Modulation of erosion on steep granitic slopes by boulder armoring, as revealed by cosmogenic Al-26 and Be-10. Earth Planet. Sci. Lett. 186 (2), 269–281.
Hall, K., Thorn, C.E., Sumner, A., 2012. On the persistence of "weathering." Geomorphology 149–150, 1–10.
Harris, R.C., Pearthree, P.A., 2002. A home buyer's guide to geological hazards in Arizona. Arizona Geological Survey Down-To-Earth, 13, pp. 1–36.
Holt, W.E., Chase, C.G., Wallace, T.C., 1986. Crustal structure from 3-dimensional gravity modeling of a metamorphic core complex: a model for uplift, Santa Catalina-Rincon Mountains. Ariz. Geol. 14 (11), 927–930.
House, P.K., 2005. Using geology to improve flood hazard management on alluvial fans: an example from Laughlin Nevada. J. Am. Water Res. Assoc. 41 (6), 1431–1447.
Howard, A.D., Selby, M.J., 2009. Rock slopes. In: Parsons, A.J., Abrahams, A.D. (Eds.), Geomorphology of Desert Environments. Springer, New York, pp. 189–232.
Hyeres, A.D., Marcus, M., 1981. Land use and desert dust hazards in central Arizona. Geol. Soc. Spec. Pap. 186, 267–280.
Idso, S.B., Ingram, R.S., Pritchard, J.M., 1972. An American haboob. Bull. Am. Meteorol. Soc. 53 (10), 930–935.
Iverson, R.M., 2005. Debris-flow mechanics debris-flow hazards and related phenomena. In: Savage, W., Baum, R. (Eds.), Instability of Steep Slopes. Debris-Flow Hazards and Related Phenomena. Springer, Berlin, pp. 53–79.

Jakob, M., Hungr, O., 2005. Debris-Flow Hazards and Related Phenomena. Springer, Berlin.
Kesel, R.H., 1977. Some aspects of the geomorphology of inselbergs in central Arizona, USA. Z. Geomorph. 21, 119–146.
Larson, P.H., Dorn, R.I., Palmer, R.E., Bowles, Z., Harrison, E., Kelley, S., Schmeeckle, M.W., Douglass, J., 2014. Pediment response to drainage basin evolution in south-central Arizona. Phys. Geogr. 35 (5), 369–389.
Larson, P.H., Kelley, S.B., Dorn, R.I., Seong, Y.B., 2016. Pediment development and the pace of landscape change in the northeastern Sonoran Desert, United States. Ann. Assoc. Am. Geogr. 106, 1195–1216.
Liu, T. VML Dating Lab. http://www.vmldating.com/, 2017.
Liu, T., Broecker, W.S., 2007. Holocene rock varnish microstratigraphy and its chronometric application in drylands of western USA. Geomorphology 84 (1), 1–21.
Liu, T., Broecker, W.S., 2008. Rock varnish microlamination dating of late Quaternary geomorphic features in the drylands of the western USA. Geomorphology 93 (3), 501–523.
Liu, T., Broecker, W.S., 2013. Millennial-scale varnish microlamination dating of late Pleistocene geomorphic features in the drylands of western USA. Geomorphology 187, 38–60.
Lozano-García, M.S., Ortega-Guerrero, B., Sosa-Nájera, S., 2002. Mid-to late-Wisconsin pollen record of San Felipe Basin Baja California. Quat. Res. 58 (1), 84–92, 9.
Marcus, M.G., Brazel, A.J., 1992. Summer dust storms in the Arizona Desert. In: Janelle, D.G. (Ed.), Geographical Snapshots of North America. Guilford Press, New York, pp. 411–415.
McAuliffe, J.R., Van Devender, T.R., 1998. A 22,000-year record of vegetation change in the north-central Sonoran Desert. Palaeogeogr. Palaeoclimatol. Palaeoecol. 141 (3), 253–275.
Melton, M.A., 1965. Debris-covered hillslopes of the southern Arizona desert: consideration of their stability and sediment contribution. J. Geol. 73 (5), 715–729.
Michael, D.R., Cunningham, R.B., Lindenmayer, D.B., 2008. A forgotten habitat? Granite inselbergs conserve reptile diversity in fragmented agricultural landscapes. J. Appl. Ecol. 45 (6), 742–752.
Molnar, P., Anderson, R.S., Andersson, S.P., 2007. Tectonics, fracturing of rock, and erosion. J. Geophys. Res. Earth 112 (F3)doi: 10.1029/2005JF000433.
Nagy, M.L., Pérez, A., Garcia-Pichel, F., 2005. The prokaryotic diversity of biological soil crusts in the Sonoran Desert (Organ Pipe Cactus National Monument AZ). FEMS Microbiol. Ecol. 54 (2), 233–245.
Nations, D., Stump, E., 1981. Geology of Arizona. Kendall Hunt, Dubuque.
Oberlander, T.M., 1989. Slope and pediment systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology. Belhaven Press, London, pp. 56–84.
Ollier, C.D., 1965. Dirt cracking: a type of insolation weathering. Aust. J. Sci. 27 (8), 236–237.
Page, K.J., Dare-Edwards, A.J., Owens, J.W., Frazier, P.S., Kellett, J., Price, D.M., 2001. TL chronology and stratigraphy of riverine source bordering sand dunes near Wagga Wagga, New South Wales. Austr. Quat. Int. 83, 187–193.
Parsons, A.J., Abrahams, A.D., 1984. Mountain mass denudation and piedmont formation in the Mojave and Sonoran Deserts. Am. J. Sci. 284 (3), 255–271.
Parsons, A.J., Abrahams, A.D., Howard, A.D., 2009. Rock-mantled slopes. In: Parsons, A.J., Abrahams, A.D. (Eds.), Geomorphology of Desert Environments. Springer, New York, pp. 233–263.
Pearthree, P.A., Demsey, K.A., Onken, J.A., Vincent, K.R., House, P.K., 1992. Geomorphic assessment of the flood-prone areas on the southern piedmont of the Tortilita Mountains, Pima County, Arizona. Arizona Geological Survey Open File Report 91-11, pp. 1–32.
Pelletier, J.D., 2010. How do pediments form? A numerical modeling investigation with comparison to pediments in southern Arizona USA. Bull. Geol. Soc. Am. 122 (11–12), 1815–1829.
Penck, W., 1924. Die Morphologische Analyse: Ein Kapital der physikalischen Geologie. Engelhorn, Stuttgart.
Peterson, F.F., Bell, J.W., Dorn, R.I., Ramelli, A.R., Ku, T.L., 1995. Late Quaternary geomorphology and soils in Crater Flat, Yucca Mountain area, southern Nevada. Geol. Soc. Am. Bull. 107 (4), 379–395.
Péwé, T.L., Péwé, R.H., Journaux, A., Slatt, R.M., 1981. Desert dust: characteristics and rates of deposition in central Arizona. Geol. Soc. Spec. Pap. 186, 169–190.
Reynolds, S.J., 1985. Geology of the South Mountains, Central Arizona. Arizona Bureau of Geology and Mineral Technology Bulletin, 195.
Rhoads, B.L., 1986. Flood hazard assessment for land-use planning near desert mountains. Environ. Manage. 10 (1), 97–106.
Richards, S.M., Reynolds, S.J., Spencer, J.E. Pearthree, P.A., 2000. Geologic Map of Arizona. Arizona Geological Survey Map M-35, 1 sheet, scale 1:1,000,000.

Seong, Y.B., Dorn, R.I., Yu, B.Y., 2016a. Evaluating the life expectancy of a desert pavement. Earth Sci. Rev. 162, 129–154.

Seong, Y.B., Larson, P.H., Dorn, R.I., Yu, B.Y., 2016b. Evaluating process domains in small granitic watersheds: case study of Pima Wash, South Mountains, Sonoran Desert USA. Geomorphology 255, 108–124.

Spencer, J.E., 1984. The role of tectonic denudation in warping and uplift of low-angle normal faults. Geology 12 (2), 95–98.

Stuckless, J.S., Sheridan, M.F., 1971. Tertiary volcanic stratigraphy in the Goldfield and Superstition Mountains. Ariz. Geol. Soc. Am. Bull. 82 (11), 3235–3240.

Sutfin, N.A., Shaw, J.R., Wohl, E.E., Cooper, D.J., 2014. A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona USA. Geomorphology 221, 164–175.

Thornbush, M., 2015. Geography, urban geomorphology and sustainability. Area 47 (4), 350–353.

Twidale, C.R., 1981. Granitic inselbergs: domed, block-strewn and castellated. Geogr. J. 147, 54–71.

Twidale, C.R., 1982. Granite Landforms. Elsevier, Amsterdam.

Twidale, C.R., 2002. The two-stage concept of landform and landscape development involving etching: origin, development and implications of an idea. Earth Sci. Rev. 57 (1), 37–74.

Van Devender, T.R., 1990. Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico. In: Betancourt, J.L., Van Devender, T.R., Martin, P.S. (Eds.), Packrat Middens: The Last 40,000 Years of Biotic Change. University of Arizona Press, Tucson, pp. 134–165165.

Viles, H.A., 2008. Understanding dryland landscape dynamics: do biological crusts hold the key? Geogr. Compass 2 (3), 899–919.

Viles, H.A., 2013. Linking weathering and rock slope instability: non-linear perspectives. Earth Surf. Proc. Landf. 38 (1), 62–70.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science 351 (6269), aad2622_1–aad_1622.

Webb, R.H., Magirl, C.S., Griffiths, P.G., Boyer, D.E., 2008. Debris flows and floods in southeastern Arizona from extreme precipitation in late July 2006 Magnitude, frequency, and sediment delivery. U.S. Geological Survey Open-File Report 2008-1274, 1–95.

Youberg, A., Cline, M.L., Cook, J.P., Pearthree, P.A., Webb, R.H., 2008. Geological mapping of debris-flow deposits in the Santa Catalina Mountains, Pima County Arizona. Arizona Geological Survey Open File Report 08-06, 1–47.

Further Reading

McKenna-Neuman, C., Maxwell, C., 2002. Temporal aspects of the abrasion of microphytic crusts under grain impact. Earth Surf. Proc. Land. 27, 891–908.