Geomorphic and physiographic characteristics and processes of the Walnut Gulch Experimental Watershed, Arizona, United States

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Abstract. The Walnut Gulch Experimental Watershed, southeastern Arizona, USA, is in the Basin and Range Physiographic Province. Major geomorphic features of the watershed are results of tectonics, mostly long-term faulting, and erosion processes that have displaced and modified rocks ranging in age from Precambrian to Recent; included are the Dragoon Mountains, the Tombstone Hills, the Tombstone Surface, the Whetstone Pediment, and the drainage network of Walnut Gulch. Small-scale landforms of the watershed are individual hills, undissected remnants of alluvial fans (fan terraces), basin floors, alluvial fans, and recent alluvial sediment of stream channels, flood plains, and terrace-inset deposits.

1. Introduction

The Walnut Gulch Experimental Watershed ("the watershed") of the Southwest Watershed Research Center (SWRC), is in Cochise County, Arizona (Pl. 1a, Renard and others, this volume). It is in the Basin and Range physiographic province, which presently dominates much of southwestern North America and was formed through a series of tectonic events starting in Precambrian time and culminating in the Tertiary Period (table 1). The watershed can be described generally as an actively eroding alluvial-fan surface; however, the geomorphology of the watershed is complex. The landforms and landform surfaces of the watershed are products of geologic conditions in the watershed, the physiography of southeastern Arizona, the geologic (particularly orogenic and epeirogenic) history of the area, and the processes of soil formation, erosion, sedimentation, pedimentation, and stream incision (see especially Osterkamp and Miller, this volume, and Breckenfeld and Osterkamp, this volume).

Walnut Gulch is a major tributary of the upper San Pedro River (Pl. 1b, Renard and others, this volume), entering it from the east. The 149-km^2 watershed is equipped with numerous rain gages and 15 runoff flumes in 12 intensively studied sub-basins to support hydrologic, erosion, and ecosystem research. In addition to sensor-based data, information and maps describing geology (rock types, structural relations, and geologic history), landforms, geomorphic processes, and soil relations are critical research resources. The earliest maps and descriptions were produced during regional explorations in advance of intensive European settlement ( ), and later to support mineral exploration ( ). Watershed instrumentation was initiated in 1953, and detailed geologic and geomorphic maps were drawn ( ). In addition, the SWRC maintains an extensive historic air photo collection, a set of 1:5000 scale ortho-topo maps covering the watershed, and 1:1000 scale ortho-topo maps covering sub-watersheds.

An investigation was initiated in 1996 to expand baseline information of watershed characteristics. Watershed geomorphology was evaluated based on previously published work ( ) and new maps were drawn. Mapping was accomplished through field investigations augmented by 1:24,000-scale aerial-photograph interpretations and 1:5000-scale GIS techniques. Rock exposures, alluvial deposits, and landforms constituting topographic relief in the watershed were the focus of the mapping. Field studies of the landforms and geomorphic processes examined erosional and depositional surfaces on hillslopes, fan terraces, and at river banks, gullies, and road cuts. Separate deposits of conglomerate and overlying alluvium in the watershed are interpreted from characteristics of tectonic disturbance, soil texture and development, degree of carbonate cementation, particle-size distribution, and source rocks contributing to the deposits. The resultant maps depicting geologic units (Osterkamp and Miller, this volume) and soils (Breckenfeld and Osterkamp, this volume) and geomorphic interpretations presented in this manuscript are consistent with previous interpretations, with a few noted exceptions.

2. Geomorphology

The effects of tectonic activity, weathering, and erosion on the sedimentary, plutonic, and volcanic rocks of the Walnut Gulch watershed are exhibited by its large-scale landforms and dissected erosion surfaces (Pl. 3). At the upper end of the watershed, crystalline rocks vulnerable to chemical weathering underlie an area of pediment along the west flank of the Dragoon Mountains (Pl. 1b, Renard and others, this volume). High-relief areas of the Tombstone Hills, south of Tombstone (Pl. 1b, Renard and others, this volume), are sites of bedrock exposure that directly reflect the complex history of crustal disturbance coupled with variations in resistance to rock weathering, erosion, and soil erodibility. Mostly in the southeastern part of the watershed, the S O Volcanics weather and erode to rounded hills, and dissection of fanglomerate beds in northern parts of the watershed show the effects of late-Cenozoic regional uplift and base-level adjustment. Geomorphic results of geologic events are summarized in Table 1.

Table 1. Summary of Geologic Events in the Walnut Gulch Experiment Watershed and the Resulting Geomorphic Effects.

Geologic Time	Geologic Events	Geomorphic Effects	Comments
Precambrian	Plutonic activity; folding, faulting	Initiation of fracture patterns	At least one in watershed
Paleozoic	Marine transgression	Flat clastic and carbonate rocks	Mostly marine deposits
Mesozoic	Compressional block faultng	Fault-block relief, erosion	Deposition, Bisbee Group
	Igneous activity	Plutonic rocks, Tombstone Hills	Mineralization at faults
	Erosion of fault blocks	Deposition of Bisbee Group	Clastics fining upwards
Mesozoic, late	Regional overthrust faulting	Formation of Tombstone Hills	Due to plate tectonics
		Initiation of Tombstone Surface	Erosion, fan deposits
Tertiary	Tensional block faulting	Basin and Range topography	Erosion, fan deposits
		Rhyolite; hills of S O Volcanics	Erosion, fan deposits
		Development, Dragoon Pediment	Surface of transport
		Development, Whetstone Pediment	Surface sedimt transport
Tertiary, late	Tilting, faulting of fan deposits	Start, much of drainage network	Deposition inset sediment
	Epeirogenic uplift	Incision by San Pedro River	Headward erosion
		Deposition of inset alluvium	Jones Ranch Alluvium
Holocene, late	Drought; human settlement	Renewed channel incision	By runon from above

2.1 Physiography

The San Pedro River Basin, including the Walnut Gulch watershed, is in the Basin and Range Physiographic Province. Mountains of the Basin and Range Province typically are large fault blocks of Paleozoic sedimentary rocks and younger igneous-intrusive and volcanic rocks. The troughs separating the tensionally constructed fault blocks are filled with Tertiary-age beds of silt, sand, and gravel derived from erosion of the mountain blocks.

Owing to late-Mesozoic movement of thrust plates over faulted rocks of the San Pedro River Valley (Pl. 1b, Renard and others, this volume) and subsequent covering of the plates in many places by fan deposits, some Basin and Range block faults remain obscured. A conceptualization by Stewart (1980), however, suggests that the southern Dragoon Mountains signify a horst, the San Pedro River occupies a graben, and at least two half-graben blocks separate the mountains and the river. A series of stair-steps above the river resembles large-scale stream terraces in this part of southeastern Arizona. This pattern may indicate removal of fan deposits from fault-block surfaces by late-Quaternary downcutting of the San Pedro River (Cooley, 1968), possibly corroborating the model proposed by Stewart (1980).

2.2 Large-scale Landforms

During and after episodes of Cenozoic deformation and faulting, the fan deposits and adjacent bedrock areas were erosionally planed to pediments sloping gently from mountain fronts toward the San Pedro River. The pediments resulted from long-term wearing back and beveling at the bases of the fault blocks; thus, the pediments were surfaces of sediment transport, slowly eroding into and over the bedrock. The early stage of pedimentation was one of planation of sediment deposited as the Emerald Gulch and Gleeson Road Conglomerates and was followed by late-Cenozoic incision of the conglomerates and local re-deposition of the sand and gravel as the Jones Ranch Alluvium and Holocene alluvium.

The exposure of pre-Cenozoic rocks by Basin and Range faulting caused rapid erosion and deposition of the Gleeson Road Conglomerate. Accompanying the erosion processes was development during the Pliocene of the Tombstone Surface and the Whetstone Pediment (Menges and Pearthree, 1989) (Pl. 3). The magmas and mineral-rich veins in the Tombstone Hills, which during Mesozoic and early Cenozoic time had moved upward along the older complex of faults (Drewes, 1981), also were partially beveled by erosional processes.

In the Walnut Gulch area Bryan (1926) identified (1) a Tombstone Pediment, largely a surface (Pl. 1) on variable thicknesses of Gleeson Conglomerate veneering eroded bedrock in the Tombstone Hills south of Walnut Gulch, and (2) a Whetstone Pediment (Pl. 2), which slopes westward from the northern and central Dragoon Mountains, is 15 to 30 meters lower than the Tombstone Surface, and formed on tilted beds of the Gleeson Road Conglomerate. Headward extension by the Walnut Gulch drainage network dissected and isolated bedrock exposures and deeply incised the Tombstone Surface and rocks of the thrust plate upon which it formed. The Whetstone Pediment merges gradationally with the higher Tombstone Surface north of Walnut Gulch, possibly as subtly developed fan terraces associated with the east-west faulting as inferred by Gilluly (1956) and Spangler (1969). Alternatively, the Paleozoic and Mesozoic rocks, combined with later igneous intrusions, that were thrust into the present Tombstone Hills area formed a topographically high area. Erosion, much more as incision than of pedimentation, since the overthrusting occurred no doubt reduced the extent of bedrock exposures. The landforms of the Tombstone Hills, however, are fundamentally different from those of dissected fan deposits to the north, and generally do not include surfaces of sediment transport. Distinguishing the feature as a pediment, as did Bryan (1926), therefore, may be erroneous.

Plate 1 Photograph southward showing sparse grasses and shrubs on the upper Whetstone Pediment in the foreground and the Tombstone Hills in the distance; the dark band between them, in front of the Tombstone Hills, is vegetation on the Tombstone Surface

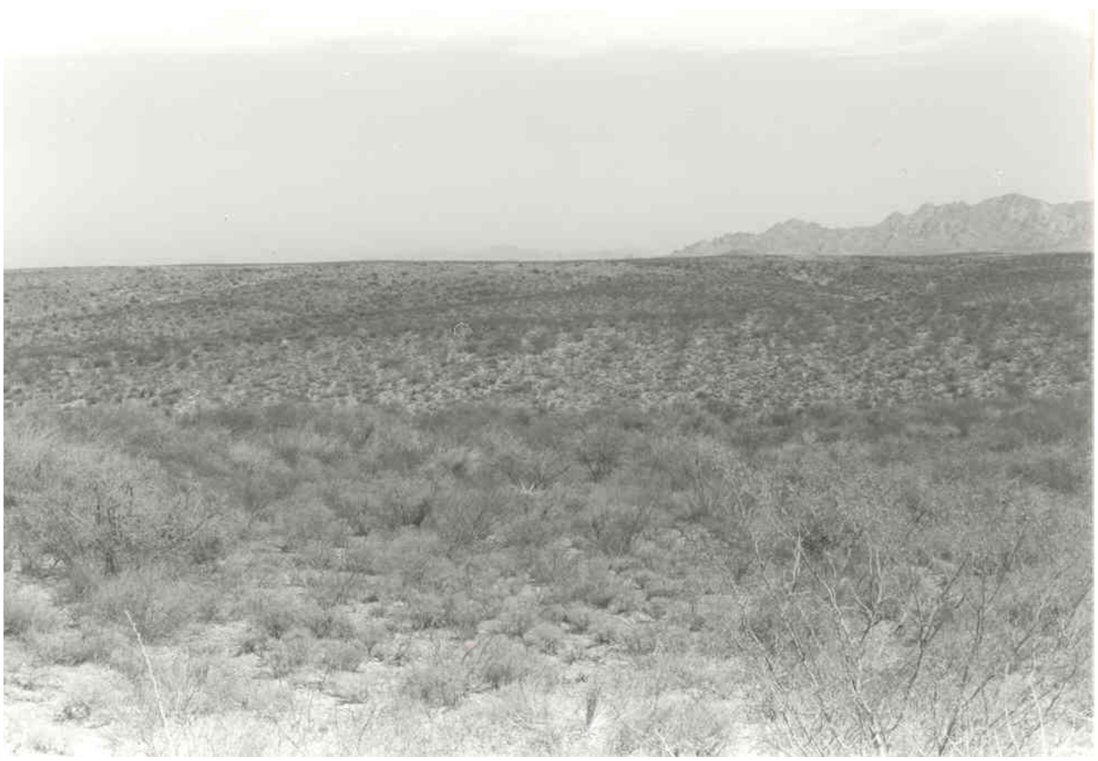

Plate 2. View to the northeast showing the northern Dragoon Mountains in the middle right. The horizon on the left, extending to the right in front of the mountains, is the surface of the upper of the upper Whetstone Pediment, in front of which, in mid-picture, is a mature drainage incising beds of the Gleeson Road Conglomerate. Vegetation is dominantly grasses and creosotebush (*Larrea tridentata*).

Well logs and seismic profiles (Spangler, 1969) from near Flume 1 show that about 50 m of conglomerate overlie Uncle Sam Porphyry, suggesting that the area is part of the Tombstone Hills complex. Schieffelin Granodiorite at Flume 2 (Pl. 1c, Renard and others, this volume) and well records showing it at shallow depth also indicate Tombstone Hills complex. The seismic studies of Spangler (1969), however, suggest that the Naco Group is at shallow depth near Flume 2. One to 2 km downstream, the Bisbee Group is faulted to within 70 m of the surface. A 100-m well south and downstream of Flume 6 (Pl. 1c, Renard and others, this volume) penetrated only Gleeson Road Conglomerate, suggesting that it is on the north, downthrown side of a fault and on the Whetstone Pediment. Locally, as in the Lucky Hills area (Pl. 1c, Renard and others, this volume), gullies deeply incise the Whetstone Pediment, much of the erosion having occurred during the last 130 years. In higher parts of the watershed, between the Dragoon Mountains and Tombstone, dissection has been less intense, especially recently, than it has been in lower parts of the watershed. In the San Pedro River trough, both the Whetstone Pediment and the Tombstone Surface are covered by Holocene alluvium.

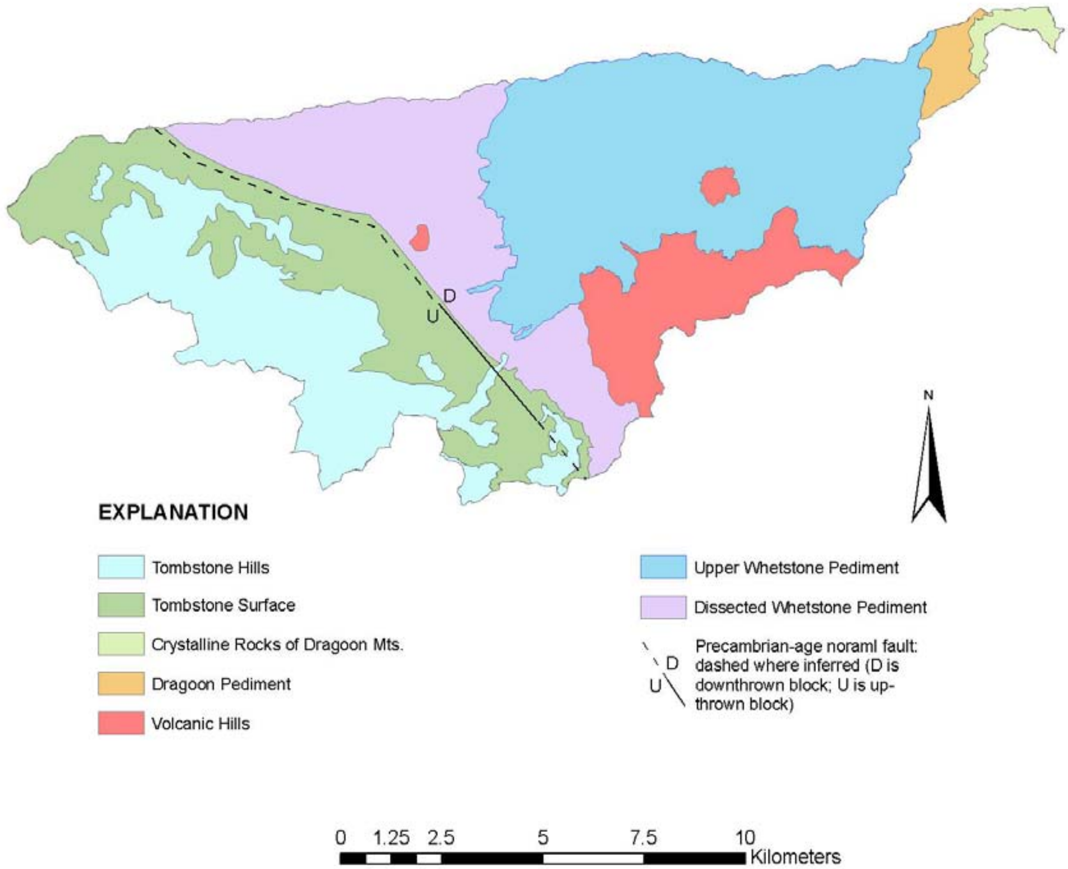

Plate 3. Map showing major geomorphic features of the Walnut Gulch Experimental Watershed including bedrock areas of mountains and hills, areas of erosional surface and pediment, and a high-angle normal fault .

Pediments and other surfaces of planation in arid or semiarid regions typically develop gentle slopes on bedrock or older, partially consolidated, alluvial deposits. In the Walnut Gulch watershed, most areas of pediment are on tilted strata of the Gleeson Road Conglomerate that were beveled by erosion into a gently sloping surface that later was dissected by stream-channel incision progressing eastward from the San Pedro River. Other pediments, near to and adjoining the Dragoon Mountains, the Tombstone Hills, and exposures of volcanic rocks, expand largely by headward fluvial erosion into the bases of bedrock hills, forming and maintaining abrupt and slowly receding fronts or escarpments.

Thus, both process sets of pedimentation yield low-relief surfaces of uniformly gentle slope, or ones that are slightly concave upward, on which erosion is minimal and the sediment supplied to the upper margin of the surface from the bedrock exposures moves downslope with little or no permanent storage. Channel incision of a pediment may occur following renewed uplift of the bedrock area or by downcutting of the principal stream at the downslope end of the pediment, causing a lowering of base level. In the Walnut Gulch watershed, lowering of the San Pedro River has resulted in headward extension and dissection of pediment surfaces along Walnut Gulch and its tributaries.

The Dragoon Pediment (Pl. 2), the lower limit of which is inferred, occurs as a relatively narrow band along the western base of the Dragoon Mountains and in the Walnut Gulch watershed has developed on quartz monzonite and sheared gneissic granite that originally may have been rock exposures of the mountain front. The Tombstone Surface, as previously described, is a complex of erosional terraces capping variable thicknesses of fan deposits overlying Paleozoic and Mesozoic rocks that form the Tombstone Hills. The Tombstone Hills area generally is at higher elevation than surrounding areas, resulting in relatively high-energy conditions and deep incision of the fan deposits adjacent to exposed bedrock. Thus, areas underlain by Gleeson Road Conglomerate around the Tucson Hills are regarded here to be erosion surfaces and not surfaces of transport (portions of a pediment).

The structurally lower Whetstone Pediment lies to the north and east of the Tombstone Surface. The transition between the two is indistinct but generally is near Walnut Gulch and closely parallels the long-active, northwest-trending, high-angle fault that was interpreted by Gilluly (1956) and mapped by Drewes (1981) (Pl. 2). The Whetstone

Pediment is entirely on fan deposits and throughout the watershed has been dissected by a drainage network initiated by mid- to late-Cenozoic extensional faulting (Menges and Pearthree, 1989) and enhanced by regional epeirogenic uplift during late-Quaternary time.

The eastern component of the pediment, the upper Whetstone Pediment (Pl. 3), is partially dissected, mostly as a result of erosive runon from the Dragoon Mountains and upper parts of the pediment. The western portion, termed the Dissected Whetstone Pediment, has been well dissected by runon from higher parts of the pediment, headward extension of tributaries due to late-Quaternary lowering of the San Pedro River (Cooley, 1968), and renewed river and tributary incision following concentrated livestock grazing and related human stresses on the channel system beginning about 130 years ago (Pl. 3). The narrow zone separating the two components of the pediment closely conforms to the change from soils of the Sutherland-Mule-Tombstone Group to those of the Luckyhills-McNeal Group (Breckenfeld and Osterkamp, this volume, Pl. 1). Owing probably to the degrees of channel incision and dissection in the two components, the easternmost exposures of Emerald Gulch Conglomerate are at the boundary separating the two parts. Plant cover also appears to reflect the intensity of erosion, the upper Whetstone Pediment being dominated by grasses and by trees at higher elevations, whereas the Dissected Whetstone Pediment typically has sparse grasses but abundant whitethorn acacia (*Acacia constricta*) and creosotebush (*Larrea tridentata*).

2.3 Small-scale Landforms

Landforms of the Walnut Gulch watershed were categorized by Breckenfeld (1994) as hills and mountains (including isolated or individual hills or mountains), fan terraces, alluvial fans, basin floors, and flood plains. These landforms are products of fluvial erosion, deposition, and related hillslope processes, and hence they and the soils that veneer them reflect late-Quaternary climate and climate variability. A unique suite of soil types is associated with each landform category.

Hills and mountains in the Basin and Range Physiographic Province of southeastern Arizona range from steep, site-specific erosional features that supply sediment from bare rock surfaces to upland surfaces of low to moderate slope upon which erosion is less intense and generally thin argillic (enriched in silicate-clay) soils may accumulate. Slope steepness is largely a function of the ability of a bedrock type to resist chemical weathering, and the intensity by which a hill or mountain has been affected by faulting and folding. Principal examples of this type of landform in the Walnut Gulch watershed are small areas granitic and gneissic rocks of the Dragoon Mountains, rounded hills formed of the S O Volcanics in the southeastern part of the watershed, and surfaces underlain by mostly carbonate, volcanic, and igneous-intrusive rocks in the Tombstone Hills.

Fan terraces, as defined by Breckenfeld (1994), are remaining surfaces of alluvial fans that have had stream incision since the end of fan deposition. The remnant surfaces, therefore, overlie generally mature argillic soils and are interrupted by escarpments with thinner and less mature soils that slope down toward the channels that have dissected the fan deposits. In a related discussion on the geology of the Walnut Gulch watershed (Osterkamp and Miller, this volume), the fan deposits that are capped by fan terraces are described as the uppermost beds of the Gleeson Road Conglomerate; the large-scale surfaces that have been dissected are the Whetstone Pediment and the Tombstone Surface.

Mid-Holocene to recent accumulations of basin-fill, alluvial-fan, and flood-plain deposits described by Breckenfeld (1994) in the Walnut Gulch watershed are restricted to partially closed basins, locales adjoining upland bedrock surfaces, and terrace and inset sediment, sand and gravel bars, and stream gravel within fan incisions. These deposits, which are grouped as the Jones Ranch Alluvium and late-Holocene alluvium (Osterkamp and Miller, this volume) originate from mountains, hills, and other up-slope sources, and generate permeable, very immature, sandy-loam soils that may be susceptible to covering or modification by subsequent episodes of channel erosion or sedimentation.

2.4 Drainage Development and Geologic Controls on Erosion

The large-scale crustal disturbances that started in southeastern Arizona in Precambrian time and have continued to the present, have controlled drainage patterns of the area; each tectonic pulse altered the stream network that previously had prevailed. The present drainage patterns of the San Pedro and Walnut Gulch Basins were imposed initially by the extensional faulting that began in mid-Cenozoic time (Menges and Pearthree, 1989). Regional epeirogenic uplift in late-Quaternary time caused incision by the San Pedro River, which resulted in elevated energy conditions along tributaries, including Walnut Gulch (Cooley, 1968). The combined effects of (1) base-level lowering by the river, (2) headward erosion by tributaries, (3) downstream erosion by runoff from the Dragoon Mountains and the Tombstone Hills, (4) structural control of stream channels, and (5) recent landscape stress possibly due to drought, floods, and human settlement explain why the Whetstone and Tombstone Surfaces of the Walnut Gulch Basin and elsewhere are now deeply incised.

The Walnut Gulch watershed is atypical of those heading in mountains. The uppermost part is anomalously small and narrow due to the tectonic history, especially of the thrust faulting that moved older rocks northeastward onto younger rocks (Drewes, 1981). The drainage divide at the southeastern edge of the watershed is largely determined by S O Volcanics, and exposures of the Naco and Bisbee Groups and the Uncle Sam Porphyry in the Tombstone Hills largely define the southwestern divide. The northern drainage divide is the result of long-term drainage-network evolution, but also may suggest separate fault blocks.

Stream-channel positions in the Tombstone Hills area mostly have been determined by the complex of faults and folds, which have been altered further by igneous activity and hydrothermal changes to adjacent rocks. The positions of much of Javelina Draw, for example, which enters Walnut Gulch from the south in section 31, T. 19 S., R. 22 E. (Pl. 1c, Renard and others, this volume), appears to be determined by faults and possibly folding. Drainage-basin evolution in the northern part of the watershed underlain by Gleeson Road Conglomerate has been strongly affected by the same fault systems that control drainage patterns elsewhere, but conclusive field evidence for many of the faults is lacking.

Reaches of Walnut Gulch where fault control has been established by field observations or is strongly suspected owing to channel morphology and alinement include (1) sites of abrupt shift in channel direction from north-northwest to west-southwest back to north-

northwest immediately south of the basalt exposure and upstream of Flume 6 (Gilluly, 1956; Drewes, 1981), (2) a straight, northwest-trending 1½-km length immediately downstream from Flume 6, (3) the area of Naco Group exposures upstream from Flume 2 (Gilluly, 1956), and (4) short, straight channel lengths oriented west, then north, downstream from Flume 2. Fractures clearly control channel position along a tributary to Walnut Gulch at Flume 5 (Alonso, 1997).

2.5 Recent Erosion, Sedimentation, and Geomorphic Research

Recent analyses of atmospherically deposited cesium-137 on the shrub-dominated Lucky Hills sub-watershed have indicated patterns and rates of soil erosion and redistribution of sediment relative to similar analyses for a grass-dominated area. Elevated hillslope erosion rates in the shrub-dominated sub-watershed were largely attributed to vegetation and were correlated with rock in the upper soil profile; they were not correlated, however, with slope or land curvature (Nearing and others, 2005; Ritchie and others, 2005). Field experiments to quantify plot-scale hillslope erosion rates have been the focus of rainfall simulations (Paige and others, 2003). Simulations conducted across a range of sites on the watershed revealed strong associations between rainfall and soil and cover types. Rock fragments significantly affect hillslope erosion on the watershed where rock cover, or desert pavement, has developed as water has moved small soil particles downslope while leaving the rock fragments on the surface (Simanton and Toy, 1994; Simanton and others, 1994).

Sediment yields from small watersheds have been quantified through accumulation surveys of sediment in stock tanks starting in the late 1950s. Sediment-accumulation records of 30 to 47 years recently were updated and evaluated for sub-watersheds ranging in area from 0.35 to 1.6 km^2. Within the 149-km^2 watershed, sediment yield from the sub-watersheds ranged from about 63 to 375 (metric) tons per square kilometer per year (t km^{-2} yr^{-1}), with a mean of 175 t km^{-2} yr^{-1} and a standard deviation of 125 t km^{-2} yr^{-1}. Although sediment yields were temporally and spatially variable, with the exception of runoff volume, no significant relations were found to explain sediment-yield variability; characteristics of channel-network development, however, probably influence sediment transport and storage dynamics (Nichols, 2006).

In addition to plot, hillslope, and small-watershed research, the watershed is instrumented to measure sediment flux at small flumes draining areas of 0.5 to 11.2 ha (hectares). Prior to the mid-1980s, fluvial sediment was collected at several large flumes. Sediment export rates from eight unit-source sub-watersheds recently were evaluated for the period 1995 through 2005. The data were used to develop statistical relations between flow characteristics and sediment concentrations, and between total event sediment exports to event runoff characteristics (Nearing and others, this volume). In 2002, research to quantify the contributions of coarse sediment to total sediment load was initiated and pit traps were installed below the overfall of flumes to measure runoff at the outlets of two small sub-watersheds. Preliminary results of this ongoing research indicate that as much as 15 percent of the total sediment transported during a flow event is not sampled (Nichols, 2003).

Compilations of sediment-discharge data (Osterkamp, 1999) do not adequately characterize sediment-yield variations in the Walnut Gulch watershed, but investigations by Renard and others (1993) indicate that a major control of sediment-yield variation in recent decades has been land use. Gully erosion in the Lucky Hills area of the northern part of the watershed (Pl. 1c, Renard and others, this volume), for example, probably began due to heavy grazing and high-magnitude storms in the late 1800s and early 1900s. Photographs suggest that channel incision in the Lucky Hills was intense in the 1930s and that channel erosion remains active 70 years later. Although difficult to document, variation in geology, thus soils, very likely influences sediment yields in the Walnut Gulch watershed. Research currently is being conducted to quantify the influence of geomorphology on soil erodibility (Rhoton and others, in press).

Computed sediment yields, for varying periods, from 15 sub-basins of the watershed vary from 40 to 370 (metric) tons per square kilometer per year (t km^{-2} yr^{-1}) (Osterkamp, 1999). The highest yields were in the northern watershed where gully erosion continues to incise fan deposits. The lowest yields also were from fan deposits in the northern watershed at sites not yet degraded by gully erosion. Sparse data from an unnamed tributary to Walnut Gulch heading near the south-central basin divide suggest that sediment yields from areas of the Naco Group and the S O Volcanics are low, approximately 50 to 60 t km^{-2} yr^{-1}.

Recent research to understand the geomorphic evolution of the main stem of Walnut Gulch has revealed a pattern of increasing vegetation and narrowing of primary flow paths within the broader alluvial channel (Nichols and Renard, this volume). Since the 1970s, these changes have been coincident with reductions in the number and magnitudes of floods. Cyclic patterns of channel narrowing and widening and aggradation and degradation are anticipated in response to periods of drought and above-average precipitation. The cycles are important controls of short-term sediment transport and storage within the channel network.

Understanding the causes of erosion, measuring sediment movement, and developing a process based understanding of erosion, transport, and deposition are fundamental research goals in the Walnut Gulch Experimental Watershed. Imposed disturbance of the last 130 years has been a major determinant of erosion and sediment flux, hillside and bottomland sediment storage, and its removal from storage in the drainage network. The effects of geology and soils, topography, semiarid climate, and native Desert Plains Grassland vegetation, however, also strongly influence sediment movement in the watershed and are more easily quantified than is the effect of land use.

In sub-basins, therefore, where human disturbance is minimal but where surface geology is dominated by a small range of rocks types, discharge data are vital resources upon which other watershed research relies. Especially useful could be flow and sediment-concentration data from sub-watersheds throughout the basin that are underlain primarily by (1) Paleozoic carbonate rocks (mostly in the Tombstone Hills), (2) S O Volcanics (in the southeast), (3) the Bisbee Group (in the southwest), (4) the Schiefflin Granodiorite (in the west), and (5) the Uncle Sam Porphyry (in the extreme southwest). Expanding the current instrumentation network to further the direct collection of water- and sediment-discharge data, supplemented with measurements of sediment stored in reservoirs and time-integrated changes of sediment storage along stream channels, seems mandatory for the acquisition of variable-source flux information supporting other research in the watershed.

3. Summary Statement

The geology and thus the landforms of the Walnut Gulch watershed are very complex, and an understanding of the events that led to the complexity helps explain the mineralization of the Tombstone Hills, the unique form and drainage pattern of the watershed, and especially why rainfall/runoff relations and sediment yields of the watershed are highly variable. The synopsis of the geology provided here is based partly on basin-specific field observations but mostly on published reports of areas in the American Southwest larger than the Walnut Gulch watershed. Data provided in the reports are more detailed than were possible to collect for this investigation. Some of those reports, cited previously, have contributed substantially to understanding the geology of the Tombstone area. All, however, became dated upon publication. A reasonably complete geologic knowledge of the Walnut Gulch watershed, therefore, has not yet been achieved. Nevertheless, each study adds to the fund of information, and the generalizations provided herein will be modified as future investigations document the geologic history of the area better than now. Meanwhile, it is hoped that this summary can help guide near-term activities for other field investigations and erosion-modeling efforts dependent on geologic information, and thus provide the foundation for progress in those studies.

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