Geology, Soils, and Geomorphology of the Walnut Gulch Experimental Watershed, Tombstone, Arizona

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Abstract

The surface geology of the Walnut Gulch Experimental Watershed (WGEW), Tombstone, Arizona, is dominated by fan deposits, but in southern and southeastern parts of WGEW a complex history of tectonism has resulted in igneous-intrusive and volcanic rocks, and highly disturbed Paleozoic and Mesozoic rocks in the Tombstone Hills. Soils, which are dominantly sand and gravel loams that vary from deep and well drained to thin and immature, are reflective of the rocks on which they formed. Large landforms are mostly dissected pediments and erosion surfaces, and hills of the volcanic and carbonate rocks. Episodic faulting that began in Precambrian time has resulted in complex geologic and geomorphic conditions that remain poorly understood owing to Basin and Range structural and depositional processes. 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. This paper combines the results of previous studies with recent field investigations and analysis of aerial photography to yield a summary of watershed conditions in support of ongoing research.

Introduction

The Walnut Gulch Experimental Watershed (WGEW) is part of the U.S. Department of Agriculture (USDA) Agricultural Research Service's (ARS) Southwest Watershed Research Center (SWRC), Tucson, AZ (Fig. 1). Walnut Gulch is a major tributary of the upper San Pedro River, entering it from the east. The 150-km^2 watershed is equipped with 88 rain gages and 15 runoff flumes in 12 intensively studied subwatersheds; numbered flumes, such as number 10, cited herein refer to the drainage area of the respective subwatersheds designated by a five-digit number starting with 63.0 (Fig. 1). A principal goal is to relate rainfall, runoff, and sediment yield to land use through erosion modeling. To meet this goal, basic knowledge of watershed characteristics is essential. Information describing geologic (rock types, structural relations, and history), landform- and geomorphic-processes, and soil relations is no longer adequate to meet the research objective. An investigation was initiated in 1996 to compile expanded baseline information of watershed characteristics. The field-based investigations have been augmented by the use of aerial photography, imagery analysis and GIS techniques, and by integrating available information with recently published data and interpretations of those data.

Accompanying maps of WGEW depict soil distributions and geomorphic features resulting from erosional and depositional processes. Aerial photography, 1:24,000 scale, was used for the mapping; additional analysis was based on 1:5000 orthophotographs. Rock exposures, sediment, and landforms constituting topographic relief in WGEW were the focus of the mapping. Field studies of the geology and geomorphology examined rock and soil exposed on hillslopes and at river banks, gullies, and road cuts. Mapped contacts are based on field observations and previous geologic investigations, but are inferred where masked by soil, vegetation cover, or human activities. Separate deposits of conglomerate and overlying alluvium in the watershed are interpreted from characteristics of tectonic disturbance, soil development, degree of cementation, particle-size distribution, and source rocks contributing to the deposits.

Geology

The geology of WGEW is expressed by consolidated rocks and fan and alluvial deposits that range in age from Precambrian to Recent. Except for modern deposits, all of the rock units have been complexly faulted and folded during a series of tectonic episodes that resulted in a Basin and Range physiography, emplacement of igneous intrusive and extrusive rocks, and the occurrence of related mineral deposits of the Tombstone Hills, south of Tucson (Fig. 1).

Rock Units

Rock types in WGEW include lithified sedimentary, plutonic, and volcanic rocks, and fan deposits and alluvium, with varying degrees of calcrete cementation, derived from weathering of exposed rocks (Fig. 2). The sedimentary, plutonic, and volcanic rocks range in age from Precambrian through late Cenozoic and were displaced by moderate to major tectonism. Detailed descriptions of the petrology, age, geologic history, and chemistry of these formations are reported by, among others, Gilluly et al. (1954), Gilluly (1956), Bryant (1968), Drewes (1981), and Force (1996).

Lithified Sedimentary, Plutonic, and Volcanic Rocks. The oldest rock unit of the Walnut Gulch Basin is an unnamed, Precambrian gneissic granite exposed near the headwaters area of the Dragoon Mountains (Gilluly 1956, p. 13). The sheared granite forms much of the grass-covered pediment at the base of the Dragoon Mountains. Stratigraphically higher and exposed only in

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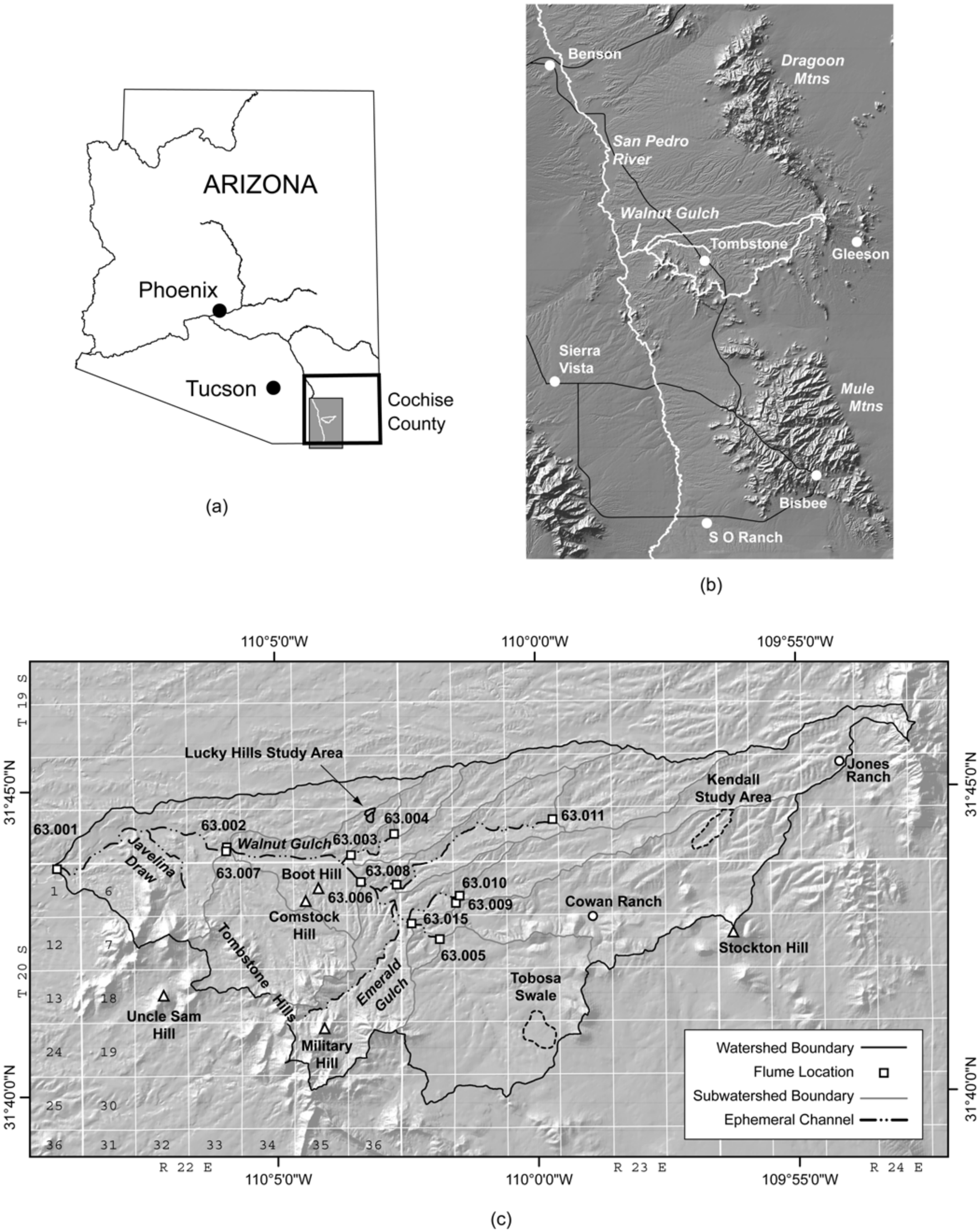

Figure 1. *Walnut Gulch Experimental Watershed location maps.*

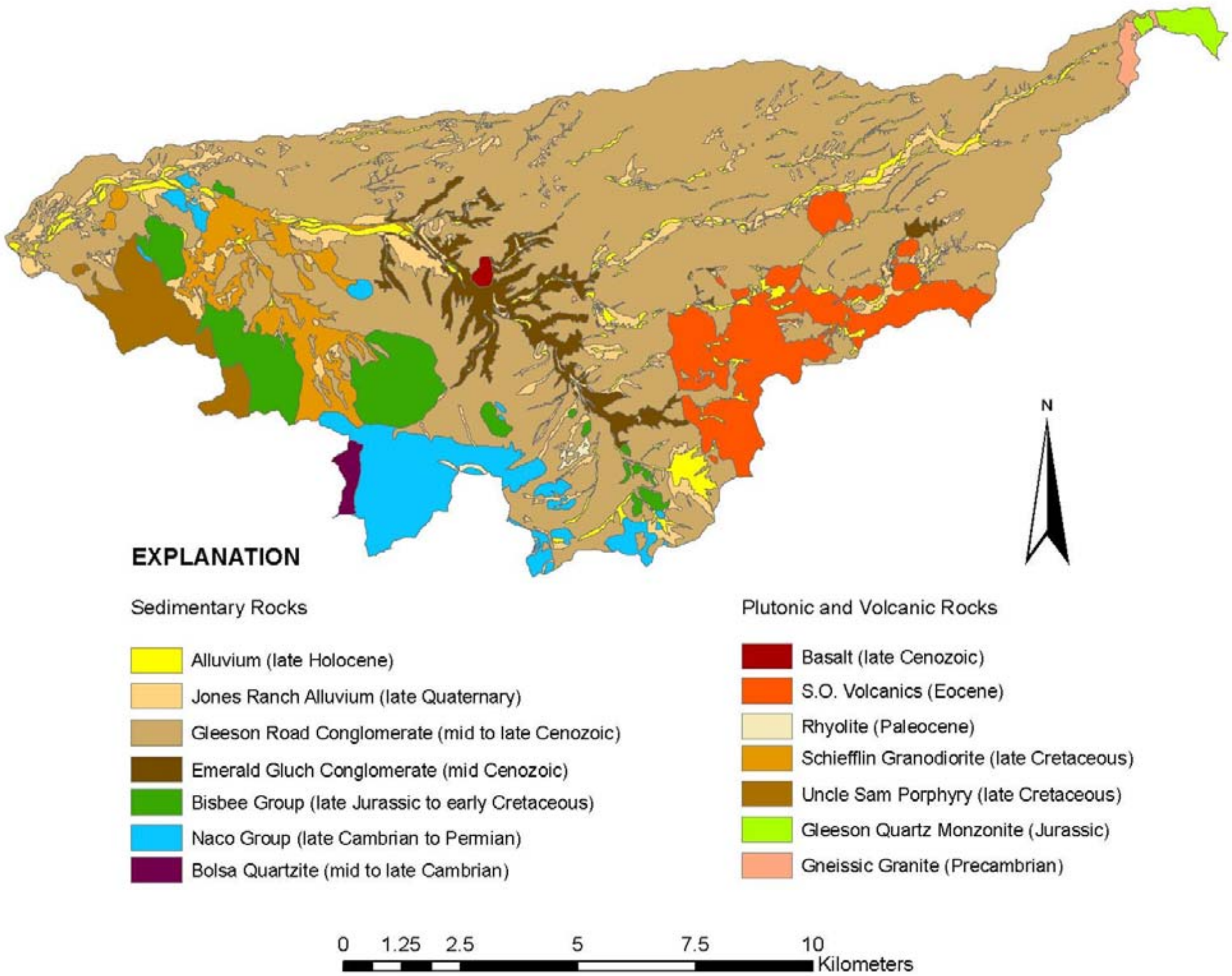

Figure 2. *Geologic map of the Walnut Gulch Experimental Watershed.*

a north-south band about a kilometer west of Military Hill (mostly in sections 14, 15, 22, 23, and 27, T. 20 S., R. 22 E.) (Fig. 1c) is the middle- to late-Cambrian Bolsa Quartzite, a littoral, transgressive-sea sand and gravel deposit (Bryant 1968). Crossbedding is common in the formation, the lower part of which typically is coarse grained and rich in feldspar, whereas the finer-grained upper part contains little feldspar (Krieger 1968). The most erosion-resistant formation of the Tombstone area, the Bolsa Quartzite forms high ridges and part of the southwestern basin divide (Fig. 2).

Marine limestones, with interbedded shale, sandstone, and dolomite, were deposited intermittently from late-Cambrian through Permian time; in ascending order they are the Abrigo (late Cambrian), Martin (Devonian), and Escabrosa (early Mississippian) Limestones, and the Horquilla Limestone (Pennsylvanian), Earp Formation (Pennsylvanian/Permian), Colina Limestone (Permian), and Epitaph Dolomite (Permian), which comprise the Naco Group. These Paleozoic carbonate rocks were moved to their present positions in late-Cretaceous time by regional occurrences of widespread Laramide overthrusting (Drewes 1981) and form hillslopes and erosion surfaces near the western and southern limits of WGEW.

Outcroppings of Abrigo Limestone and Martin Limestone, which is easily eroded and forms gentle slopes (Gilluly et al. 1954), are at the same north-striking folds where the Bolsa Quartzite occurs. The upward sequence continues eastward with the Escabrosa Limestone at the top of Military Hill and a larger area of Horquilla Limestone, which fills a faulted syncline, immediately to the east. The crinoid-rich, thick-bedded Escabrosa Limestone resists erosion and forms conspicuous, poorly vegetated cliffs of the higher hills (Gilluly et al. 1954, Bryant 1968). The Horquilla Limestone is the most widespread of the Paleozoic carbonate formations, underlying most of the eastern part of the Tombstone Hills; owing to numerous soft, thin shale beds, it erodes readily to gently sloping hills (Bryant 1968). The uppermost formations of the Naco Group, the Earp Formation, the Colina Limestone, and the Epitaph Dolomite, are exposed only in small areas of the Tombstone

Hills. The Earp Formation is on a part of the downthrown block of the high-angle Prompter thrust fault, a kilometer north of Military Hill. The Colina Limestone is widespread and resistant to erosion in the Tombstone Hills (Gilluly et al. 1954) and is faulted to the surface north of Walnut Gulch a kilometer upstream from Flume 2. Exposures of the lower part of the Epitaph Dolomite are resistant to erosion and form cliffs, whereas the upper part has thin shale and limestone beds that readily erode (Gilluly et al. 1954). The aptly named Epitaph Dolomite forms much of Comstock Hill (and nearby “Boothill”) northwest of Tombstone and also outcrops immediately north of the Colina Limestone near Flume 2.

A small area at the base of the southern Dragoon Mountains is underlain by the Gleeson Quartz Monzonite, an easily weathered, coarse-grained stock rich in quartz, plagioclase, hornblende, and biotite. An erosion-resistant alaskitic facies of the Gleeson Quartz Monzonite occurs in the uppermost WGEW and supports an oak woodland canopy. Largely by radiometric dating (K-Ar) of biotite in rock samples from the Tombstone Hills and Dragoon Mountains, Hayes and Drewes (1968) assigned a mid-Jurassic age to plutons such as the Gleeson Quartz Monzonite; this conclusion was supported by Anderson (1968), who determined an age of 178±5 M years from K-Ar dating of muscovite taken from the monzonite. Later, Drewes (1976) used K-Ar dating to establish an early Jurassic age for the Gleeson Quartz Monzonite.

Beds of the late Jurassic to early Cretaceous Bisbee Group unconformably overlie the overthrust carbonate rocks of the Tombstone Hills in the southwestern part of WGEW (Hayes and Drewes 1968, Force 1996). Reactivation of Precambrian age, northwest-trending faults in early Mesozoic time caused increased relief near the faults. Basal deposits resulting from the renewed movements were thick, coarse conglomerates and sandstones. Widely distributed and generally alternating arkosic sandstones, deltaic sandstones, mudstones, and limestones grade upwards in the Bisbee Group, reflecting lowered energy conditions (Drewes 1981, Force 1996).

The principal hosts for the silver deposits and related minerals of the Tombstone mining district are beds of the Bisbee Group offset by high-angle faults and injected by quartzitic veins (Force 1996). Where thermally altered in the Tombstone Hills, strata of the Bisbee Group are resistant to erosion and may form ridges, but otherwise the beds weather to rounded hills less prominent than those of nearby calcareous rocks (Gilluly 1956). Most outcroppings of the Bisbee Group in WGEW are alined roughly from a small patch about 8 km southeast of Tombstone to larger areas of exposure 2 km southeast of and directly south of Tombstone. A large area of Bisbee Group sub-parallels Walnut Gulch south and west of Tombstone, and the most northerly outcroppings are related to faulting adjacent to Walnut Gulch upstream 2 to 3 km from Flume 2 (Fig. 2).

Named for Uncle Sam Hill on the divide 5 km southwest of Tombstone, the Uncle Sam Porphyry is a resistant quartz-latite to quartz-monzonite porphyry underlying much of the southwestern Tombstone Hills and extending northward at least to Flume 2 (Fig. 2). Using radiometric dating, Marvin et al. (1973) determined a late Cretaceous age for the Uncle Sam Porphyry. In the Tombstone Hills the Uncle Sam Porphyry erodes to rugged escarpments, but to the southwest it is exposed as dissected pediment. Much of the Uncle Sam Porphyry is an extrusive rock body that locally overlies the Schieffelin Granodiorite and thus may be equivalent in age (Force 1996). With its quartz, feldspar, and corundum phenocrysts, it intrudes older, underlying rocks of the Tombstone area but to the southwest of WGEW the porphyry is cut by and thus is of similar age or slightly older than adjacent emplacements of Schieffelin Granodiorite (Gilluly 1956).

The feldspar-rich, quartz-poor Schieffelin Granodiorite locally grades to a quartz monzonite (Gilluly 1956). It is closely related in age to the ore deposits 1 to 4 km southwest and west of Tombstone. As are other rock units of WGEW, the Schieffelin Granodiorite is roughly oriented northwest, alined with the fault system of the Tombstone Hills. The northernmost exposure, at Walnut Gulch upstream from Flume 2, overlies faulted Paleozoic rocks. Although a K-Ar date of biotite from the Schieffelin Granodiorite gave a late Cretaceous age similar to the Uncle Sam Porphyry (Creasey and Kistler 1962), its stratigraphic position above the Uncle Sam Porphyry and below the oldest fan deposits of WGEW indicates that it is slightly younger than the Uncle Sam Prophyry. Owing to relatively high susceptibility to chemical breakdown, the Schieffelin Granodiorite weathers to subdued erosion surfaces that slope generally northeastward from the Tombstone Hills toward Walnut Gulch.

Several small masses of resistant rhyolite intrude the Paleozoic limestones and form topographic highs and part of the basin divide in the southern part of WGEW. The unnamed intrusions are sills and dikes up to 150 m in thickness (Gilluly 1956). Biotite from the rhyolite yielded a K-Ar date of 63 M years, indicating a very early Paleocene age (Creasey and Kistler 1962). The rhyolite intrusions overlie complexly folded and faulted beds of Paleozoic carbonate rocks, mostly of the Colina Limestone, 6 to 7 km south of Tombstone in section 31, T. 20 S., R. 23 E.

The S O Volcanics, named for exposures at S O Ranch (not shown) 13 km east of Tombstone, are thick quartz-latite tuffs and hornblende-andesite flows that are distributed along the southeastern basin margin from Stockton Hill (section 7, T. 20 S., R. 24 E.) westward nearly 7 km (Fig. 2). Andesite flows, with black hornblende phenocrysts up to 30 mm in length, form rounded but prominent hills and mesas; elsewhere, relatively soft tuffs of the lower S O Volcanics erode readily and thus are rarely exposed. A sample from the tuff member yielded a K-Ar date of about 47 M years, or mid-Eocene in age (Marvin et al. 1973). The S O Volcanics are low to intermediate in density and contribute to a gravity low beneath exposures east of the Tombstone Hills (Spangler 1969).

The youngest of the volcanic rocks in WGEW is an olivine basalt exposed along Walnut Gulch a kilometer northeast of Tombstone. The age of the basalt is not known, but because it intrudes fan deposits of likely Miocene age and is well weathered, a late Miocene or early Pliocene age is assumed. The small volcanic body is one of several of late Cenozoic age between the Dragoon Mountains and the Tombstone Hills that imply movement of lava along otherwise concealed fault zones (Drewes 1981).

Fan Deposits and Alluvium. Poorly to well-cemented alluvial deposits in WGEW include the Emerald Gulch and Gleeson Road Conglomerates (also termed fanglomerates), the Jones Ranch Alluvium, and unconsolidated stream alluvium (Fig. 2). Because exposures of the alluvial deposits are small, they often are mapped as undifferentiated alluvium. The names Emerald Gulch Conglomerate, Gleeson Road Conglomerate, and Jones Ranch Alluvium, which were suggested by M. A. Alonso as alternatives to her previous designations of Alluvium I, II, and III (Alonso 1997), are used herein and are intended for application only to local deposits; they have not been submitted for approval as formal geologic names.

The Emerald Gulch Conglomerate is named for exposures along lower Emerald Gulch east of Tombstone. It is the oldest of the alluvial beds, equivalent in age to the deformed fan deposits of Eocene through early Miocene age of Melton (1965) and likely to the Miocene age Pantano Formation of the Santa Cruz River Basin (Brown et al. 1966, Pool and Coes 1999), including the Tucson area (Fig. 1a). The Emerald Gulch Conglomerate is virtually limited to channel bottoms, principally at an unnamed draw heading at the southern divide of WGEW; outcroppings extend from 0.5 km downstream from a stock pond (#12, in section 20, T. 20 S., R. 23 E.) to the site of Flume 15 (NW ¼ of section 7, T. 20 S., R. 23 E.), immediately upstream from Walnut Gulch. Minor exposures, probably displaced to the surface by faulting, occur near Flumes 8 and 9. The conglomerate has massive, 1-to-2-m thick gray to white beds of gravel and cobbles separated by thin, sandy interbeds. It is well cemented with sandy calcrete of probable ground-water origin and contains clasts as large as 0.8 m of limestone and sandstone derived from the Paleozoic and Mesozoic sections and smaller fragments of volcanic rocks and flint.

Dissected beds of the mid- to late Cenozoic Gleeson Road Conglomerate, correlative with the Gila Conglomerate of Gilluly (1956), the undeformed basin fill of Melton (1965), and upper and lower basin fill of Brown et al. (1966), are widespread in WGEW. The lowermost beds of the Gleeson Road Conglomerate are inferred to be correlative to the lower basin fill of Brown et al. (1966) in the Sierra Vista area (Fig. 1b), and the upper part of the Gleeson Road Conglomerate is probably equivalent both stratigraphically and in age to the Plio-Pleistocene upper basin fill of Brown et al. (1966). To the west and northwest, along the axis of the San Pedro River Valley (Fig. 1b), the upper part of the Gleeson Road Conglomerate grades into fine-grained fluviatile and lacustrine beds of the Plio-Pleistocene St. David Formation (Gray 1965, Melton 1965).

The Gleeson Road Conglomerate is named for Gleeson Road, which traverses beds and soils derived from conglomerate eastward between Tombstone and the town of Gleeson. Most of WGEW is directly underlain by the Gleeson Road Conglomerate, exceptions being in the Tombstone Hills where carbonate, clastic, and various igneous rocks are at the surface, and in the southeastern part of the drainage basin, where S O Volcanics are exposed. The Gleeson Road Conglomerate varies in thickness from veneers overlying near-surface bedrock to at least 900 m in the north-central part of WGEW (Spangler 1969). Although Melton (1965) described it as undeformed, locally the fanglomerate is extensively fractured where underlying faults have reactivated, and at larger areal scales the formation is tilted owing to late Cenozoic fault-block movement (Stewart 1980).

Terraces of the conglomerate are underlain by a mature red to brown soil that elsewhere in the San Pedro River Valley (Melton 1965, Haynes 1968) has an age of about 30,000 years. Pronounced 20th century gullying of the mostly massive, undeformed conglomerates and poorly cemented sand and silt partings of the Gleeson Road Conglomerate is widespread. Most near-surface strata contain less than 10% carbonate (Breckenfeld 1994), and thus have low resistance to mechanical erosion. Abundant bedforms, channel-fill and alluvial-plain depositional sequences, and hydromorphic paleosols within the conglomerate indicate that WGEW, prior to settlement, was characterized by less variable discharges, deeper channels, and higher ground-water levels than those of the current drainage system.

Clasts of the Gleeson Road Conglomerate mostly are derived from nearby bedrock. Most clasts in eastern parts of WGEW are from plutonic or volcanic rocks, whereas limestone clasts predominate in the southern part. This tendency is modified where paleostreams transported coarse sediment away from the local source. Vegetation is highly variable, but grasses are typically most dense where clasts of the S O Volcanics are abundant.

The Jones Ranch Alluvium (Fig. 2), the cienega deposits of Melton (1965) and part of the pre-entrenchment alluvium of Brown et al. (1966), is transitional in age between the Gleeson Road Conglomerate and Holocene alluvium. The color is generally brownish-pink in contrast to brownish-gray of most Holocene deposits. The Jones Ranch Alluvium includes the oldest inset deposits of the present drainage system. Thus, it represents late Quaternary fan and terrace strata of silt, sand, and gravel that mostly are topographically higher than the most recent channel deposits and that were partially removed by late 19th and 20th century erosion. The channel, flood-plain, and terrace deposits of the Jones Ranch Alluvium are up to 3 m thick, may be capped by a paleosol, and, having little or no carbonate cement, are easily eroded. Included also in the Jones Ranch Alluvium are fan deposits along mountain-front faults, such as those at Jones Ranch near the headwaters of Walnut Gulch. Where fault-scarp deposition has occurred, the Jones Ranch Alluvium may be tens of meters thick.

The youngest beds of the watershed are mostly late Holocene flood-plain, bar, and channel deposits of sand and gravel. This alluvium partially refills incisions developed by post-development gully erosion. Most of the deposits are bars and terraces up to 2 m above modern stream channels, but locally, such as at the Tobosa Swale (section 21, T. 20 S., R. 23 E.) and Cowan Ranch (section 12, T. 20 S., R. 23 E.), mid- to late Holocene swamp deposits occupy closed depressions caused by late-Quaternary faulting. The alluvial and paludal (swamp) deposits typically support dense grass. Where recent gully erosion has exposed dark, carbonate-rich paludal beds at Cowan Ranch, radiocarbon dating yielded an age of about 5,200 years.

Structural Geology and Geologic History

Unlike many areas of the Basin and Range Province, much of WGEW is dominated by sedimentary rocks of the Paleozoic and Mesozoic sections, several granitic and gneissic intrusions of various ages, and a range of volcanic rocks related to block-fault tectonism. Cemented fan deposits and alluvium, typical of the Basin and Range, are at the surface in much of WGEW, but mostly as small-to-moderate thicknesses overlying bedrock.

Structural features in WGEW principally are products of tectonic episodes of Precambrian, early and middle Mesozoic, late Mesozoic to early Cenozoic, and mid-to-late Cenozoic times (Drewes 1981). Although folds and faults in Precambrian granitic rocks are difficult to recognize owing to reactivation of crustal stresses, the large-scale features, including the plutons, remain as prominent structural features reflecting early tectonism. Precambrian rocks were deformed further during Mesozoic time both by deep plutonic emplacements and by the intrusion at shallower levels of dikes and related tabular rocks.

The tectonism that resulted in the present Basin and Range physiography of southeastern Arizona began at the start of the Mesozoic Era. In early Triassic through earliest Cretaceous time, rocks of the watershed and adjacent areas were compressed, causing block faulting and a second period of intrusion by igneous masses such as the Gleeson Quartz Monzonite, the Uncle Sam Porphyry, and the Schieffelin Granodiorite. Related to igneous activity in the Tombstone Hills area was the emplacement along existing faults of mineralized quartz veins and porphyry dikes (Force 1996). The Mesozoic tectonism culminated in late Cretaceous time with regional overthrust faulting.

Starting in the early Tertiary, the last major tectonic event yielding the present topography of the Walnut Gulch area was relaxation of compressional forces that caused the Mesozoic faulting and igneous activity. The change caused southwest to northeast tension and renewed block faulting typical of the Basin and Range Province. This latest tectonic period extended into Holocene time and yielded Paleocene rhyolite flows and the Eocene S O Volcanics. In all cases of tectonism, exposed rocks were eroded, and the sediment was deposited as alluvial fans or valley fill (Drewes 1981).

The effects of tectonic events of the Walnut Gulch area, including volcanic activity and igneous intrusion, have been very complex. Faults and folds in rocks of a late Cretaceous thrust plate that partially form the Tombstone Hills are numerous and are only summarized here, and in other parts of WGEW many structural features are no doubt covered and thereby concealed by younger rocks or more recent tectonic events. Details of the structural geology of WGEW were described in previously cited reports, especially those of Gilluly (1956), Drewes (1981), and Force (1996); a regional perspective was given by Menges and Pearthree (1989).

Three major fault systems are related to the tectonic events of the watershed. The first has had recurring movements beginning in Precambrian time. The faults are mostly high-angle normal shears oriented northwest, one of which appears to extend from southeast of Bisbee to the northeast flank of the Mule Mountains, passing east of Tombstone and Benson before entering the Tucson Basin (Drewes 1981).

The second set includes the Mesozoic compressional block faults and large-scale, very low-angle late-Cretaceous thrust faults that moved Paleozoic and Mesozoic strata, locally with Precambrian crystalline rocks, northeastward up to 200 km. At least two overthrusts related to plate tectonics, indicated at field sites but not fully verified by Drewes (1981), appear to have covered WGEW and adjacent areas and moved rocks that comprise the Tombstone Hills into their present positions. The eastern edge of the second, the Cochise thrust plate, abuts the southwestern Dragoon Mountains and contains numerous folds and high-angle faults associated with the overthrust movements (Drewes 1981). The faults are common along the Dragoon Mountains, but many are concealed by sediment or are poorly exposed. Only one of the thrust faults, forming the western extent of the small outcropping of Precambrian gneissic granite, is apparent within the narrow headwater area of WGEW (Gilluly 1956, p. 13).

Regional faults of the third set are extensional, have had continuing movement since Oligocene time, and resulted in the Basin and Range topography of areas from Oregon south through Nevada into Arizona, New Mexico, and northern Mexico. The high-angle detachment faults mostly trend north, displace older structural features, and determine the landscape of the Basin and Range Province. In southeastern Arizona, the dominant trend is northwest, as shown by the alinement of the Dragoon Mountains and the Mule Mountains. None of the major Basin and Range faults is known to traverse the Walnut Gulch area, but several secondary faults may offset rocks of the watershed.

The uppermost part of WGEW is in the Dragoon Mountains, a prominent northwest-southeast range of southeast Arizona. Gilluly (1956) interpreted the Dragoon Mountains to be an individual fault-block range and identified and mapped a Dragoon fault as a suite of mostly high-angle thrust faults, some poorly exposed, along the western base of the range. Later, Drewes (1981) interpreted the high-angle faults to be secondary features of the large, compressive Cochise thrust plate; his investigations suggested that, because rocks of the Cochise thrust plate do not exhibit major fracturing, Cenozoic tensional block faulting did not occur in the underlying rocks. Based on the interpretations of Drewes (1981), therefore, it is inferred that the southern Dragoon Mountains and basement rocks beneath the Tombstone Hills east of Tombstone are parts of the same Basin and Range detachment block.

Many fracture zones beneath erosion surfaces of the watershed are complexes of high-angle thrust faults and normal faults, some of which displace Paleozoic beds of the Tombstone Hills. The largest, most well-known faults, such as the Prompter Fault about 2 km south of Tombstone, strike north-northwest. Less frequently, prominent faults strike northeast or, as does the main trace of the Prompter Fault, nearly east-west; examples that may be en-eschelon sets that also exhibit strike-slip movement are near Military Hill south of Tombstone (Gilluly 1956, pl. 5). Most of the steep faults are closely related to larger-scale Basin and Range tensional faulting or to igneous activity during the latter part of the tectonism. The combined overthrusting and extensional warping resulted in numerous small folds, seemingly randomly oriented, and several larger folds that erode to steep escarpments of the Paleozoic and Mesozoic rocks. Consequently, strikes and dips measured on folded Paleozoic rocks in the Tombstone Hills by Gilluly (1956) showed no apparent pattern.

From logs of deep wells, Gilluly (1956) inferred a concealed, east-trending fault or fault zone north of the Tombstone Hills, the northern, downthrown side of which has a much greater thickness of fan deposits than is present to the south. Spangler (1969) confirmed the conclusion with seismic profiles, one indicating a high-angle normal fault in the southwest corner of section 35, T. 19 S., R. 22 E.; the southern, upthrown block is Schieffelin Granodiorite beneath 120 m of Gleeson Road Conglomerate, whereas the north block has a large, undetermined thickness of conglomerate. Complementary with these observations, a prominent gravity "low," indicating thick alluvium, extends northwest from Walnut Gulch about 10 km east of Tombstone (Spangler 1969). Small extrusions of basalt, such as that northeast of Tombstone (Fig. 2), and apparent fault control of the Walnut Gulch channel downstream from Flume 6 are consistent with the well-log and seismic-profile evidence. Gilluly (1956) interpreted the fault to separate Basin and Range blocks, implicitly suggesting why separate erosion surfaces are apparent west of the Dragoon Mountains and in areas within and adjacent to the Tombstone Hills.

About 80% of WGEW is underlain by largely unknown thicknesses of fan deposits. The seismic-profile data of Spangler (1969), however, which mainly were from the lower part of the watershed along Walnut Gulch, indicate that thicknesses of the Gleeson Road Conglomerate south of Walnut Gulch are mostly less than 100 m, but north of Walnut Gulch they typically exceed 200 m. Beds of the fan deposits, especially of the Emerald Gulch Conglomerate, have been altered by neotectonic folding and small-scale faulting, by carbonate (calcrete) deposition, and locally by hydrothermal cementation. Typically, these fan deposits, or fanglomerates, are veneered by 1 to 6 m of Quaternary alluvial gravel that also may be well cemented by calrete (Gilluly 1956, Alonso 1997).

The episodes of Pliocene to Recent tensional stress in southern Arizona (Stewart 1980) tilted and faulted fan deposits and alluvium. The faults control channel shapes and positions of several stream reaches and the sites of former swamp deposition (Cooley 1968, Menges and Pearthree 1989, Alonso 1997). The faults also may affect transmission loss during streamflow, and thus ground-water recharge. In places, Quaternary faulting in WGEW has resulted in the deposition of fluvial and paludal beds of the Jones Ranch Alluvium in contact with older fan deposits and volcanic rocks. Downthrown fault blocks have caused local areas of subsidence, and these swale areas have become sites of swamp deposits up to 2 m in thickness.

Mapping by Force (1996) of faults, folds, and dikes of the Tombstone Hills mining district, part of which is in WGEW, identified structures in the Bisbee Group and intrusive rocks of similar age along which hydrothermal mineralization occurred. Many of the structures strike slightly east of north to N 40°E, and most show little or no relation to the drainage network. Faults striking N75°E or north to N15°E along the channel of subwatershed 63.015 displace beds of the Gleeson Road and Emerald Gulch Conglomerates and thereby determine channel positions and outcroppings of bedrock. Faults dipping 40, 75, and 50 degrees along channels of subwatersheds 63.001 and 63.009 displace the Gleeson Road Conglomerate and thus have influenced deposition of the Jones Ranch Alluvium. Many small faults in the Plio-Quaternary deposits along the San Pedro River show that the area remains tectonically active.

SOILS

Soil, as a product of natural hydrologic and geomorphic processes, is a layered mass of minerals and, generally, organic matter and rock fragments that differs from the parent material (rocks) from which it is derived in terms of morphology, physical and chemical characteristics, organisms, and organic content. The layers, or horizons, that comprise a soil are of variable thickness (as also are soil bodies), are typically but not always unconsolidated, and differ from each other in terms of degree of alteration that has occurred during the weathering process of the underlying parent material (Joffe 1949). The objectives of this part of the WGEW investigations were to interpret which variables most significantly influence soil types and distribution in the watershed, and to summarize soil characteristics relative to watershed conditions of climate, time, geology, landforms, and vegetation. In the WGEW, and many areas of southeastern Arizona, geology is inferred to exert a major control on soil distribution, maturity, thickness, and permeability. Most soils of the watershed are unconsolidated, but locally near-surface soil horizons may be moderately to well consolidated owing to the deposition of calcrete.

Soil Surveys

The Natural Resource Conservation Service (NRCS) is responsible for conducting and publishing soil surveys in the United States. The presentation of soils information has evolved from printed descriptions of pedons, tables of soil physical and chemical characteristics, and maps of soil series distributions to internet-based geographical information systems (GIS) such as STATSGO and SSURGO. The first soil survey of the WGEW was conducted by the NRCS in the late 1960s (Gelderman 1970) and contained pedon descriptions and locations of 21 soil map units. Physical and chemical properties of the soil series of the map units became available in 1974 (USDA Soil Conservation Service 1974). Currently three GIS soil surveys are available for the WGEW: STATSGO, consisting of three soil map units; SSURGO, consisting of 18 soil map units; and a more detailed survey (Breckenfeld 1994) that is based on the SSURGO data and consists of 25 soil map units <http://www.tucson.ars.ag.gov/dap/>.

Determinants of Soil Characteristics

Typically soils are regarded as products of geology and the weathering processes to which rock types are subjected. The length of time that biochemical weathering and erosion act on a parent material is also a principal determinant of soil development and thus maturity. Because topography and biology, particularly vegetation and land use, affect erosion and related hydrologic and geomorphic processes and are interactive with and dependent on geology and climate, often they too are viewed as fundamental determinants of soil genesis. More specifically, the slopes and slope lengths of landforms that define the topography of a watershed are controls of weathering rates and erosion and sediment movement from hillsides to bottomlands, and from bottomlands of the watershed to downstream parts of the drainage network. Thus, soils of the WGEW vary with components of the small-scale landforms of the watershed and their geologic characteristics.

The detailed soil surveys of the WGEW (Gelderman 1970, Breckenfeld, 1994) have demonstrated that soil types are functions of local geomorphic features, and that many soils are immature owing to semiarid climate, slow biochemical weathering, and rampant post-settlement rill and gully erosion in fan deposits north and east of Tombstone (Graf 1983). Where accelerated erosion of the last century has not stripped the upper horizons, soils tend to be thick, mature loams rich in sand and gravel and of high carbonate (calcrete) content. Virtually all of the soils reflect the underlying rocks from which they developed.

Basic controls of soil formation in the WGEW include a semiarid climate, an incomplete vegetation cover, and landform surfaces that have been exposed too little time to permit weathering to deep, mature soils. Accordingly, soils of the watershed are mostly poorly developed and strongly indicative of the rock types from which they evolved. The warm, semiarid climate of WGEW results in relatively slow biochemical reduction of bedrock. Soils of Holocene age, therefore, are typically coarse, permeable, and poorly developed. Surfaces, such as those of fan terraces, that were first exposed to weathering processes prior to Holocene time when the climate may have been more moist than now, are deeper, more mature, and generally more argillaceous than the younger soils.

The amount of time that a rock or deposit of rock fragments (such as fan deposits) is exposed to a set of climatic and biological conditions determines the texture, composition, and extent to which a soil develops on the rock or rock-deposit surface. In the WGEW, time has been inconsequential relative to soil-forming processes in areas of bare rock. In contrast, where surfaces of fan terraces remain and have been exposed to weathering processes throughout the late Cenozoic and Quaternary periods, time has been sufficient to yield deep, argillic soils, even where climatic conditions have been generally arid to semiarid. Nowhere in the watershed has time been adequate, under prevailing climates, to yield clayey soils, rich in iron and aluminum oxides and hydroxides, that are indicative of long-term warm, moist conditions.

A comparison of the soils map of the WGEW (Fig. 3) with a map of the geology (Fig. 2) suggests that areas of soil groups correlate well with bedrock outcroppings and colluvial veneers on bedrock, fan deposits, and alluvium. Specifically, areas of plutonic-rock exposures are underlain by shallow, quickly drained gravelly sand or clay loams, and hilly areas of volcanic rocks are capped by moderately deep, poorly permeable cobbly clay loams. Moderately permeable, shallow to very shallow cobbly loams are associated with limestone and dolomite of the Tombstone Hills. Soils on fan terraces of the Gleeson Road Conglomerate are typically very deep, poorly permeable gravelly sandy loams, whereas younger soils on steeper slopes of dissected beds of the Gleeson Road Conglomerate are deep, moderately permeable sandy loams and clay loams. Soils of mid-to-late Holocene alluvium are deep, well drained, and highly permeable sand loams (Breckenfeld 1994).

Remnant surfaces of the WGEW are interrupted by escarpments with thinner and less mature soils that slope down toward the channels that have dissected the fan deposits. Where capped by fan terraces, the fan deposits are the uppermost beds of the Gleeson Road Conglomerate, and the large-scale surfaces that have been dissected are either pediments or erosion surfaces. Mid-Holocene to recent accumulations of basin-fill, alluvial-fan, and flood-plain deposits described by (Breckenfeld 1994) in the WGEW 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 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.

In the WGEW the distribution and density of plant species appear to be more dependent on moisture availability and slope conditions than they are on geology. Vegetation, therefore, is a control that, like soils, varies with climate, landform, and external stresses such as land use. Of the factors that control soil development, vegetation is likely the least correlated with soil distribution in much of semiarid southeastern Arizona.

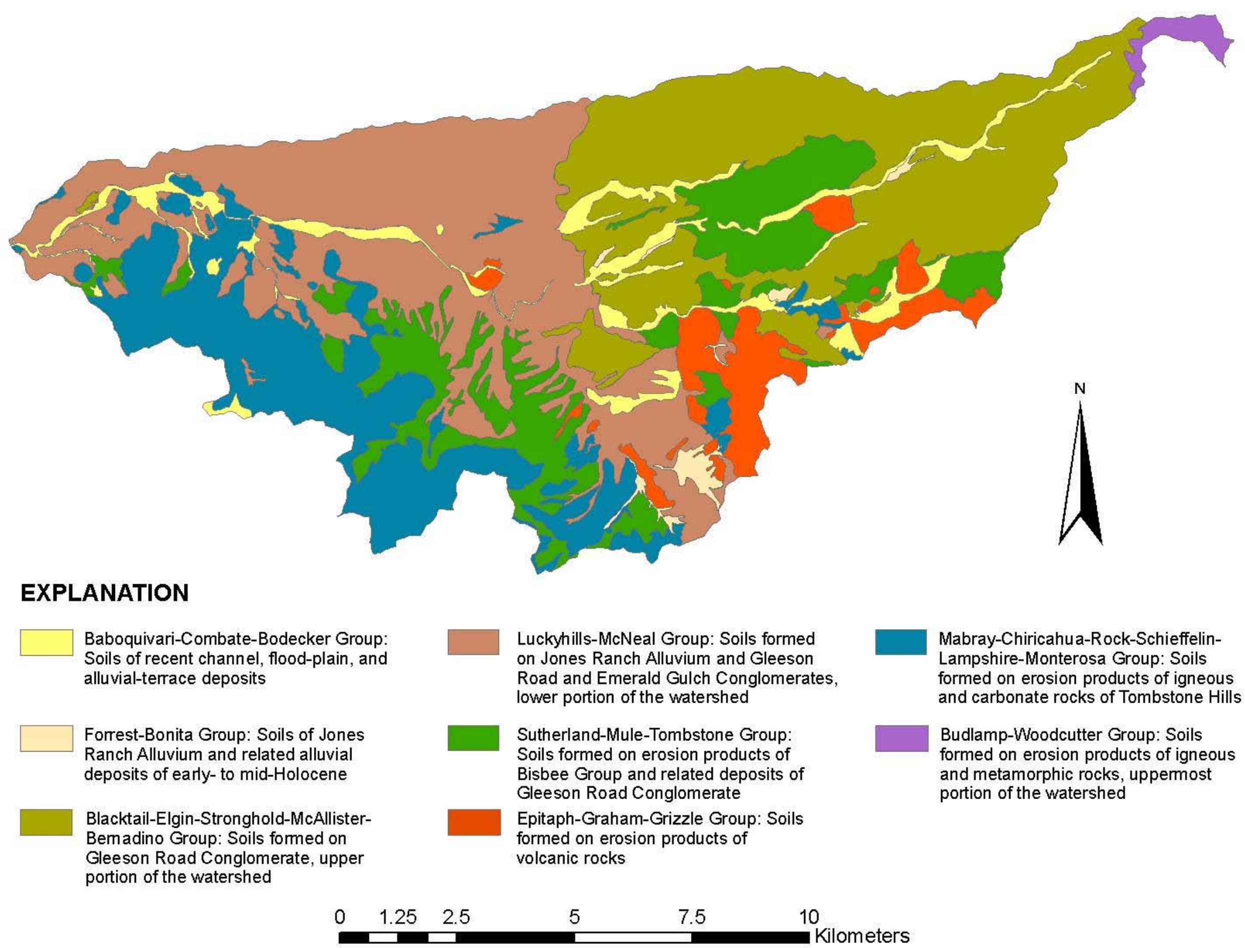

***Figure 3**. Simplified map showing distribution of soil groups in the WGEW; adapted from Breckenfeld (1994).*

Table 1. *Map units, areal extent, and textural class of soils in the WGEW based on Breckenfeld (1994).*

Map unit	Area (ha)	Percent of total area	Textural Class
Baboquivari-Combate complex	543	3.67	sandy loam
Blacktail gravelly sandy loam	245	1.66	gravelly sandy loam
Budlamp-Woodcutter complex	65	0.44	very gravelly sandy loam
Chiricahua very gravelly clay loam	147	0.99	very gravelly sandy loam
Combate loamy sand	106	0.72	loamy sand
Elgin-Stronghold complex	1,504	10.16	very gravelly fine sandy loam
Epitaph very cobbly clay loam	242	1.63	very cobbly clay loam
Forrest-Bonita complex	140	0.95	fine sandy loam
Graham cobbly clay loam	284	1.92	cobbly clay loam
Graham-Lampshire complex	244	1.65	very cobbly loam
Grizzle coarse sandy loam	81	0.55	coarse sandy loam
Lampshire-Rock outcrop complex	385	2.60	very cobbly loam
Luckyhills loamy sand	68	0.46	loamy sand
Luckyhills-McNeal complex	4,255	28.75	very gravelly sandy loam
Mabray-Chiricahua-Rock outcrop complex	495	3.35	very cobbly loam
Mabray-Rock outcrop complex	838	5.66	extremely cobbly loam
McAllister-Stronghold complex	1,358	9.17	gravelly fine sandy loam
Monterosa very gravelly fine sandy loam	284	1.92	very gravelly fine sandy loam
Riverwash-Bodecker complex	171	1.15	sand
Schiefflin very stony loamy sand	393	2.66	very stony loamy sand
Stronghold-Bernardino complex	760	5.13	very gravelly loam
Sutherland very gravelly fine sandy loam	674	4.55	very gravelly fine sandy loam
Sutherland-Mule complex	182	1.23	very gravelly fine sandy loam
Tombstone very gravelly fine sandy loam	1275	8.62	very gravelly fine sandy loam
Woodcutter gravelly sandy loam	62	0.42	gravelly sandy loam

Summary of Soil Groups

Table 1, compiled from Breckenfeld (1994), is a detailed list of soil map units in the WGEW with areal extents and textural classes, and Figure 3 is a simplified soils-distribution map, based on the pedon descriptions and soil map units of Table 1. The soil groups indicated in Figure 3 combine many of the map units of Table 1, partly to reduce map complexity and partly to illustrate the close relation that the soil units have with geology (Fig. 2).

The Baboquivari-Combate-Bodecker Group consists of permeable, immature soils formed on late Holocene channel, flood-plain, and alluvial-terrace deposits in all parts of the watershed. Mature, poorly transmissive soils of the Forrest-Bonita Group are derived principally from early to mid-Holocene cienega and inset deposits of the Jones Ranch Alluvium and weathered side-slope alluvium of recently dissected fan deposits. Large amounts of clay and silt result in the bottomland soils of the Forrest-Bonita Group being mostly clay and silt loams.

Deep sandy gravel loams of the Blacktail-Elgin-Stronghold-McAllister-Bernardino Group occur on beds of the Gleeson Road Conglomerate. The generally deep, mature soils of this group have developed slowly in areas of the upper, eastern part of the watershed where the Tombstone surface and Whetstone pediment (planation surfaces on the fan deposits) are incompletely dissected. In the lower, western part of the watershed, soils that have formed on the erosion surfaces of Jones Ranch Alluvium and the Gleeson Road and Emerald Gulch Conglomerates are in the Luckyhills-McNeal Group. Because soils of the group also are derived largely from fanglomerate beds, and because the Tombstone surface and the Whetstone pediment are more dissected in the western half of the watershed than elsewhere, the soils of the Luckyhills-McNeal Group tend to be sandy and gravelly loams that are immature compared with soils where rilling and gully erosion have been less extensive. An A horizon of these soils is typically absent, having been removed by late-Quaternary erosion (Breckenfeld 1994).

Soils of the Sutherland-Mule-Tombstone Group have developed from weathering of clastic rocks of the Bisbee Group (Fig. 2) and from conglomerate beds derived from it in areas adjacent to the Tombstone Hills and in upper parts of the watershed. The Sutherland-Mule-Tombstone soils are very gravelly, mature loams that typically contain well developed pedogenic calcrete.

Soils that have developed directly on and beside exposures of volcanic rocks, igneous and carbonate rocks of the Tombstone Hills, and igneous and metamorphic rocks in the uppermost part of the watershed include, respectively, those of the Epitaph-Graham-Grizzle Group, the Mabray-Chiricahua-Rock-Schieffelin-Lampshire-Monterosa Group, and the Budlamp-Woodcutter Group. The soils of these groups strongly reflect the rock types from which the soils formed; they have little organic matter and are almost everywhere less than 0.2 m in thickness (Breckenfeld 1994). Volcanic-terrain soils of the Epitaph-Graham-Grizzle Group, for example, are mostly thin, clay-rich loams containing abundant gravel and cobble clasts of basalt or andesite and tuff derived from the S O Volcanics. Most soils of igneous and carbonate rocks in the Tombstone Hills, the Mabray-Chiricahua-Rock-Schieffelin-Lampshire-Monterosa Group, are very immature, shallow gravel and cobble loams; exceptions are clay and gravelly clay loams of the Chiricahua Series (Breckenfeld 1994), which forms on the Bolsa Quartzite. In headwater areas of the watershed are shallow clay-, sand-, and gravel-loam soils of the Budlamp-Woodcutter Group that occur above monzonite and gneissic granite.

Geomorphology and Physiographic Characteristics and Processes

The WGEW 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 2). 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.

Walnut Gulch is a major tributary of the upper San Pedro River (Fig. 1b), entering it from the east. The earliest maps and descriptions of the physiography, geology, and landforms of the area including Walnut Gulch and the Walnut Gulch watershed were produced during regional explorations in advance of intensive European settlement (Wheeler 1875), and later to support mineral exploration (Smith 1997). The SWRC maintains a set of 1:5000-scale ortho-topo maps covering the watershed and 1:1000-scale ortho-topo maps covering subwatersheds; these maps provide detail of the drainage network and small-scale landforms of the WGEW.

The investigation that was initiated in 1996 to expand baseline information of watershed characteristics included an evaluation of geomorphology 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 were interpreted from characteristics of tectonic disturbance, soil texture and development (Fig. 3), degree of carbonate cementation, particle-size distribution, and source rocks (Fig. 2); the geomorphic interpretations presented in this section are consistent with previous interpretations, with a few noted exceptions.

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 (Fig. 4). 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 (Fig. 1b). High-relief areas of the Tombstone Hills, south of Tombstone (Fig. 1b) 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 2.

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.

***Table 2**. 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 sediment transport
		Development, Whetstone Pediment	Surface sediment 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

Owing to late-Mesozoic movement of thrust plates over faulted rocks of the San Pedro River Valley (Fig. 1b) 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).

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

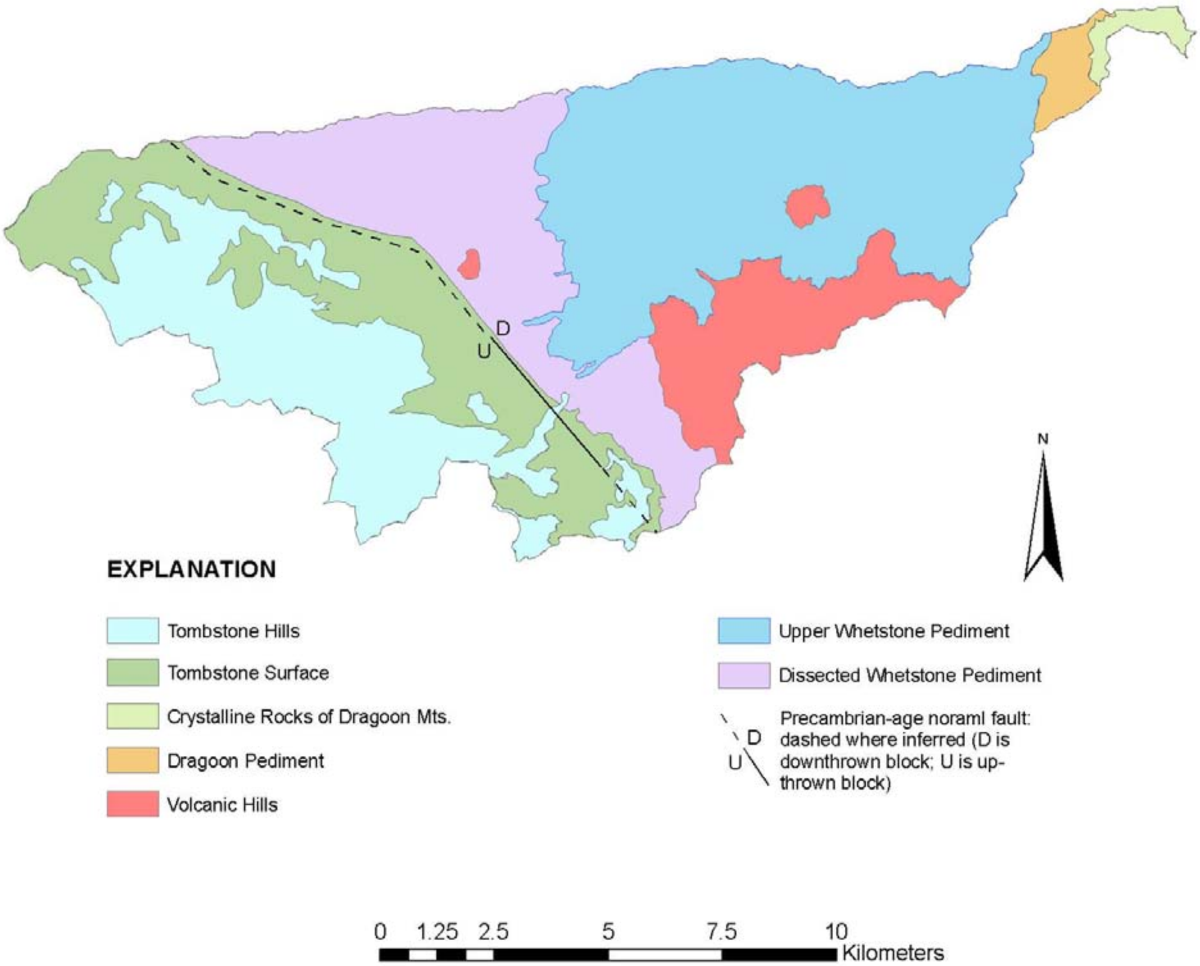

Figure 4 *Map showing major geomorphic features of the Walnut Gulch Experimental Watershed including bedrock areas of mountains and hills, areas of erosional surface and pediment, and a high-angle normal fault.*

Figure 5. *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.*

Note - the following text was omitted from the published version of this paper:

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) (fig. 4). 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 (fig. 4) on variable thicknesses of Gleeson Conglomerate veneering eroded bedrock in the Tombstone Hills south of Walnut Gulch, and (2) a Whetstone Pediment (fig. 5), which slopes westward from the northern and central Dragoon

Mountains, is 15 to 30 m 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). Gray (1965) proposed that the Tombstone Surface developed in the mid-Pleistocene, followed by erosion resulting in the Whetstone Pediment in pre-Sangamon time. 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 overthrust events 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.

Well logs and seismic profiles (Spangler 1969) from near Flume 1 (Fig. 1c) 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 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 (Fig. 1c) 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 (Fig. 1c), 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.

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 (Fig. 4), 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) (Fig. 4). 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 (Fig. 6), 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 (Fig. 4). The narrow zone separating the two components of the pediment closely conforms to the change from soils of the Blacktail-Elgin-Stronghold-McAllister-Bernardino Group to those of the Luckyhills-McNeal Group (Fig. 3). 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*).

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 of 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. As previously described, the fan deposits that are capped by fan terraces are 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, originate from mountains, hills, and other up-slope sources, and

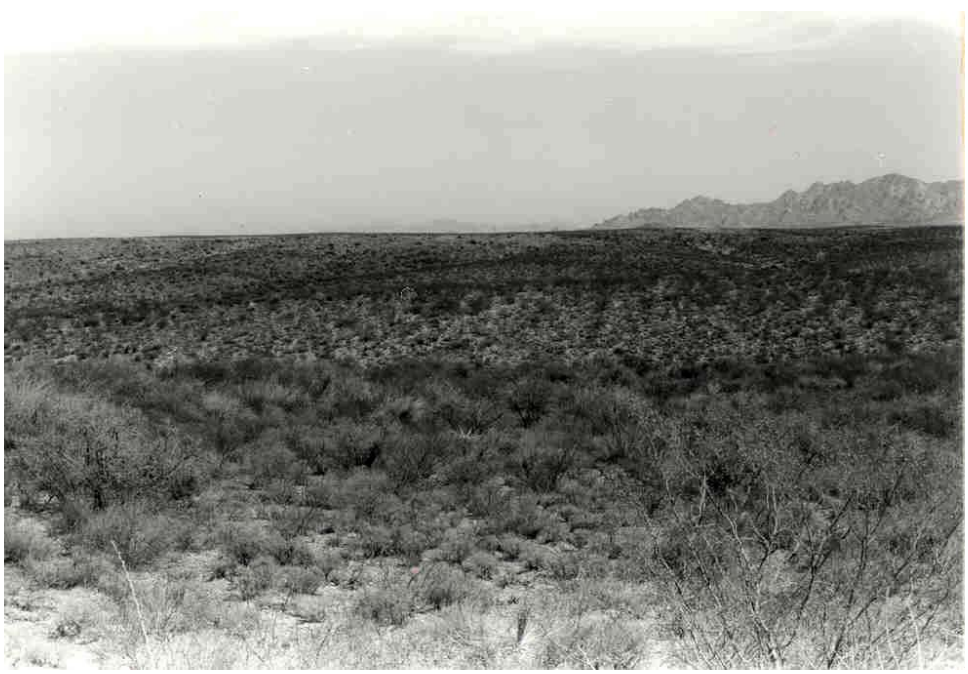

Figure 6. *View to the northeast showing the northern Dragoon Mountains in the middle right. The horizon on the left, extending to the right in front of the mountains, is the surface of the upper Whetstone Pediment, in front of which, in mid-picture, is a mature drainage incising beds of the Gleeson Road Conglomerate. Vegetation is dominantly grasses and creosotebush (*Larrea tridentata*).*

generate permeable, very immature, sandy-loam soils that may be susceptible to covering or modification by subsequent episodes of channel erosion or sedimentation.

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 32, T. 19 S., R. 22 E. (Fig. 1c), 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 alignment 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 1.5-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).

Recent Erosion, Sedimentation, and Geomorphic Research

Few interpretive studies of sediment yield from watersheds of the Southwest, including that of Walnut Gulch, are available. An investigation by Lane et al. (1997) on watershed processes that control sediment yield includes data from the WGEW. Because the data used in their analyses were similar to those considered herein, results also were similar. Ideally, validated sediment-yield data from the WGEW and similar watersheds of the Southwest can be related to measurements of sediment released by hillslope erosion to permit estimates of sediment budgets, including fluxes of sediment within a watershed and changes of sediment storage as a function of time.

Recent analyses of atmospherically deposited cesium-137 on the shrub-dominated Lucky Hills subwatershed 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 subwatershed 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 et al. 2005, Ritchie et al. 2005). Field experiments to quantify plot-scale hillslope erosion rates have been the focus of rainfall simulations (Paige et al. 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 et al. 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 150-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 subwatersheds 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 et al. 2007). In 2002, research to quantify the contributions of coarse sediment (Nichols 2004) 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 subwatersheds. Preliminary results of this ongoing research indicate that as much as 15% of the 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 et al. (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 (Fig. 1c), 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 recently has been conducted to quantify the influence of geomorphology on soil erodibility (Rhoton et al. 2007).

Computed sediment yields, for varying periods, from 15 sub-basins of the watershed vary from 40 to 370 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. 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 subwatersheds 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 Schieffelin 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.

SUMMARY STATEMENT

The geology and thus the landforms of the Walnut Gulch Experimental Watershed have been 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 and geomorphic and physiographic characteristics provided here is based partly on basin-specific field observations of rock outcroppings, soil and vegetation distributions, and geomorphic surfaces, but mostly on published reports of areas in the American Southwest larger than WGEW. 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 WGEW, 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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