Geology of the Walnut Gulch Experimental Watershed, Arizona, United States

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Abstract. The surface geology of the Walnut Gulch Experimental Watershed, Tombstone, Arizona, is dominated by fan deposits, but in southern and southeastern parts of the watershed 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 are reflective of the rocks on which they formed, and 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. 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.

1. Introduction

The Walnut Gulch Experimental Watershed ("the watershed") is part of the USDA Agricultural Research Service's (ARS) Southwest Watershed Research Center, Tucson, AZ. Walnut Gulch is a major tributary of the upper San Pedro River, 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. 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-process, 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 and -imagery analysis and GIS techniques, and by integrating available information with recently published data and interpretations of those data.

Related maps of the watershed depict soil distributions (Breckenfeld and Osterkamp, this volume) and geomorphic features resulting from erosional and depositional processes (Osterkamp and Nichols, this volume). 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 the watershed were the focus of the mapping. Place names and map coordinates given herein are shown on Plate 1 of Renard and others (this volume).

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. The names given here for fan deposits and alluvium are suggested for local application only, and have not been submitted for approval as formal geologic names.

Much of the field investigation to confirm published sources of information was conducted by Maria Angeles Alonso, Los Angeles Unified Schools, and descriptions of some alluvial deposits are her interpretations (Alonso, 1997). Field investigation was aided by Sharon Biedendbender, Ecologist, USDA Forest Service, Sierra Vista, AZ. Maps, and the digitizing of field data, were prepared by Sudhir Raj Shrestha, University of Wyoming, and by Jared Buono, Agricultural Research Service, Tucson, AZ.

2. Geology

The geology of the Walnut Gulch Experimental Watershed 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 (Pl. 1b, Renard and others, this volume).

2.1 Rock Units

Rock types in the watershed 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. 1). 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 and others (1954), Gilluly (1956), Bryant (1968), Drewes (1981), and Force (1996).

2.1.1 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 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.) (Pl. 1c, Renard and others, this volume) 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 (Keiger, 1968). The most erosion-resistant formation of the Tombstone area, the Bolsa Quartzite forms high ridges and part of the southwestern basin divide (fig. 1).

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 the watershed.

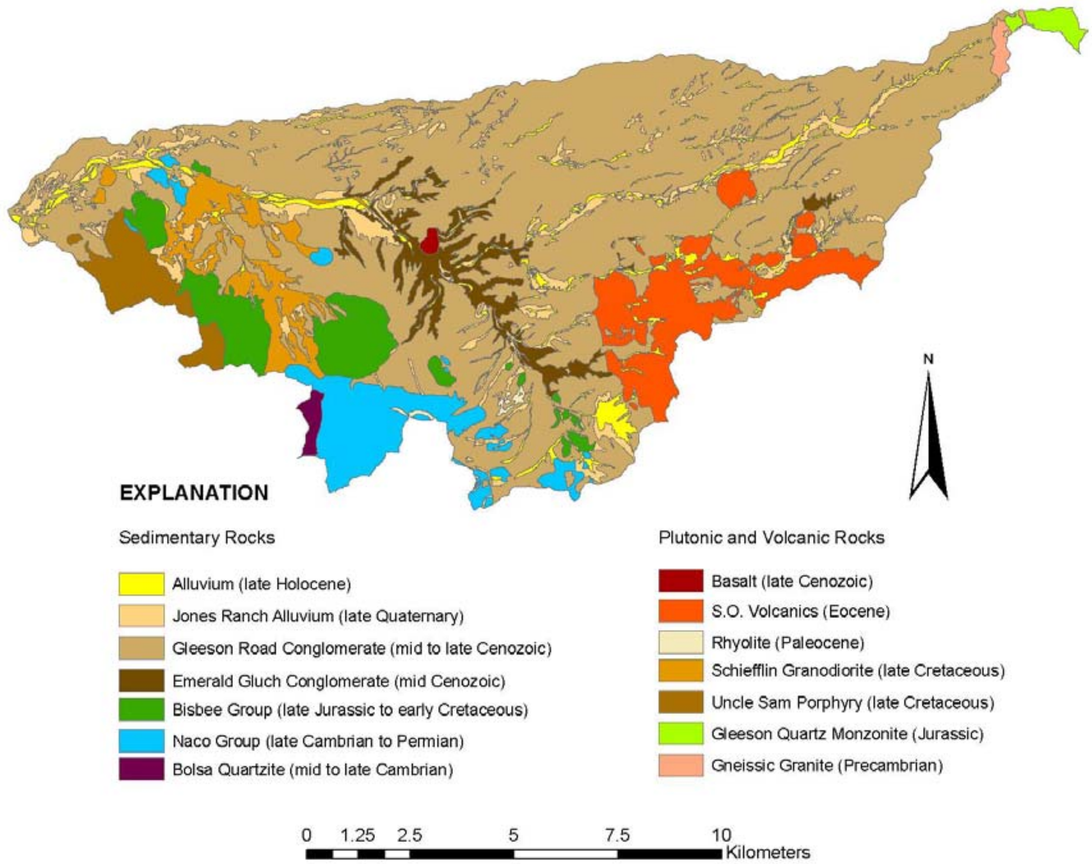

Figure 1. – Geologic map of the Walnut Gulch Experimental Watershed.

Outcroppings of Abrigo Limestone and Martin Limestone, which is easily eroded and forms gentle slopes (Gilluly and others, 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 and others, 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 (Gilully and others, 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 and others, 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 Walnut Gulch Watershed 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 the watershed (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 the watershed 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. 1).

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. 1). Using radiometric dating, Marvin and others (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 the watershed 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 the watershed, 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 the watershed 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 the watershed. 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 (Pl. 1). 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 and others, 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 the watershed 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).

2.1.2 Fan Deposits and Alluvium

Poorly to well cemented alluvial deposits in the watershed include the Emerald Gulch and Gleeson Road Conglomerates (also termed fanglomerates), the Jones Ranch

Alluvium, and unconsolidated stream alluvium (fig.1). Because exposures of the alluvial deposits are small, they often are mapped as undifferentiated alluvium.

The Emerald Gulch Conglomerate is named informally for exposures along lower Emerald Gulch east of Tombstone. Previously designated Alluvium I (Alonso, 1997), it is the oldest of the alluvial beds and is equivalent in age to the deformed fan deposits of Eocene through early-Miocene age of Melton (1965). The Emerald Gulch Conglomerate is virtually limited to channel bottoms, principally at an unnamed draw heading at the southern divide of the watershed; outcroppings extend from a half kilometer 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, the Gila Conglomerate of Gilluly (1956), undeformed basin fill of Melton (1965), and Alluvium II of Alonso (1997), are widespread in the watershed. The formation is named for Gleeson Road, which traverses beds and soils derived from conglomerate eastward between Tombstone and the town of Gleeson. Most of the Walnut Gulch watershed 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 the watershed (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 20^{th}-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 percent 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 the watershed, 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 the watershed 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. 1), the cienega deposits of Melton (1965), 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 20-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 3, T. 20 S., R. 23 E.), mid- to late-Holocene swamp deposits occupy closed depressions caused by late-Quaternary faulting. The alluvial and paludal 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 5200 years.

2.2 Structural Geology and Geologic History

Unlike many areas of the Basin and Range Province, much of the Walnut Gulch watershed 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 the watershed, but mostly as small to moderate thicknesses overlying bedrock.

Structural features in the Walnut Gulch watershed 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 the watershed many structural features are no doubt covered and thereby concealed by younger rocks or more recent tectonic events. Details of the structural geology of the Walnut Gulch watershed 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 the watershed 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 the watershed (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 the Walnut Gulch watershed 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. 1), 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 percent of the watershed 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. The faults also may affect transmission loss during streamflow, and thus ground-water recharge. In places, Quaternary faulting in the watershed has resulted in the deposition of fluvial and paludal (swamp) 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 the watershed, 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 15 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 1 and 9 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.

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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