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SURFICIAL GEOLOGY IN THE VICINITY OF WASHINGTON RANCH

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Abstract—Piedmont slopes and river terraces near Washington Ranch reflect late Neogene geologic history, but are affected by both local and regional solution subsidence of the underlying evaporitic Castile Formation. The Black River currently is a discontinuous stream with local solution sinks and springs. Holocene and late Pleistocene alluvium, marsh, and tufa deposits mark the current river level, whereas two types of older terraces are preserved in the vicinity of Washington Ranch-- fluvial gravel terraces, and a fine-grained gypsiferous "terrace" (?) deposit that indicates an episode of no coarse clastic transport along the river. Seven levels of clastic piedmont deposits with preserved surfaces ranging from highest remnants to modern tributary channels reflect changing base levels from the Guadalupe Escarpment toward the Black River and beyond. Older high piedmont levels west and northwest of the Black River cap outcrops of Castile Formation, whereas younger piedmont levels are graded close to the level modern tributaries and the Black River. The underlying Castile Formation is thinned markedly by solution and up to 100 m of coarse alluvium underlie the younger piedmont deposits, reflecting long-term subsidence of the distal parts of the piedmont and Black River. Ovoid karst features cut the piedmont deposits at all levels. Differences in spring and sinkhole water chemistries reflect different aquifers including the piedmont gravel aquifer of Rattlesnake Spring and the gypsic aquifer of Bottomless Lakes.

INTRODUCTION

Geology in the vicinity of Washington Ranch results from both local and regional processes over millions of years. The major themes, as pointed out by Hawley (1993b) are a) *tectonic* uplift and eastward tilting of the Guadalupe Mountains and Delaware Basin due to Basin and Range-related processes since mid-Miocene time; b) *surface-water* runoff, sediment transport and deposition, and establishment of streams and alluvial fans related to tectonic uplift and climate change; and c) development of separate *groundwater* flow paths within the Capitan reef, Permian evaporites, and alluvium. These separate groundwater processes resulted in acidic enlargement of large caverns in limestone and surface subsidence from solution of Permian evaporites. The major processes led to establishing the course of the Black River, differential topographic and geomorphic alluvial levels east of the Guadalupe escarpment, and clastic and chemically precipitated deposits related to development of the drainages and aquifers.

Recent age determinations for speleogenesis indicate that 1,100 m of uplift and tilting of the Guadalupe Mountains occurred in the past 12 million years (Polyak et al., 1998). The through-flowing lower Pecos River as an established base level to the east began perhaps slightly earlier, but wide-spread river terraces (Blackdom, Orchard Park and Lakewood) post-date the Gatuña Formation, which has the 640,000-year old Lava Creek B ash near its top (Bachman, 1980; Powers and Holt, 1993). Previous geomorphic work in the Washington Ranch area includes Horberg (1949) who described and correlated three generalized "terrace" units along the Black River to the terraces of the Pecos, Bachman (1980) who described regional development of the Lower Pecos River, Sares (1984) who did a detailed analysis of the geomorphology of Chosa Draw in relation to the Black River and caves of the Guadalupe escarpment, and Hawley (1993a, 1993b) who summarized the above processes, their regional effects, and preservation of different-aged deposits. Hill (1987; 1996) also related geomorphic surfaces and groundwater levels to caverns in the Capitan Reef and Permian evaporites. King (1949), Hayes (1957), and Kelley (1971) mapped old alluvium in this area as well as major bedrock features. Observations of local outcrops described for a walking tour of Washington Ranch and the road log to Slaughter Canyon, coupled with aerial photographic interpretations and topographic maps led to the somewhat speculative interpretations below.

The Black River heads in the high Guadalupe Mountains 29 km to the southwest of Washington Ranch and descends into the Delaware Basin across nested alluvial fans. The ephemeral stream presently ends in a sinkhole feature just west of the Gypsum Plain escarpment 9 km south of Washington Ranch ("Black River sink" on Fig. 1). As seen on aerial photographs, however, the course of Black River continues north to the eroded headcut at springs west of Bottomless Lakes. Perennial flowing water continues downstream to Washington Ranch, but the Black River becomes ephemeral again to the northeast until it reaches the vicinity of Black River Village. The Black River joins the Pecos River 40 km east-northeast of Washington Ranch.

PRE-QUATERNARY STRATIGRAPHY

Upper Permian bedrock underlying this reach of the Black River is the Castile Formation (Hayes, 1957; Kelley, 1971), extending from the base of the Guadalupe Escarpment (Capitan Formation) east and south into the heart of the Delaware Basin. Beneath the Castile Formation are limestones and sandstones of the Permian Delaware Mountain Group, which in turn are underlain by a thick succession of older Paleozoic carbonate and clastic rocks form a thick section below that. The Bell Canyon Formation of the Delaware Mountain Group descends about 150 m down the northwest-trending, northeast-dipping Huapache monocline beneath Washington Ranch (Kelley, 1971; Hill, 1996). The Huapache flexure is developed in late Paleozoic rocks and is cored by a northeast-vergent Pennsylvanian thrust fault with over 600 m

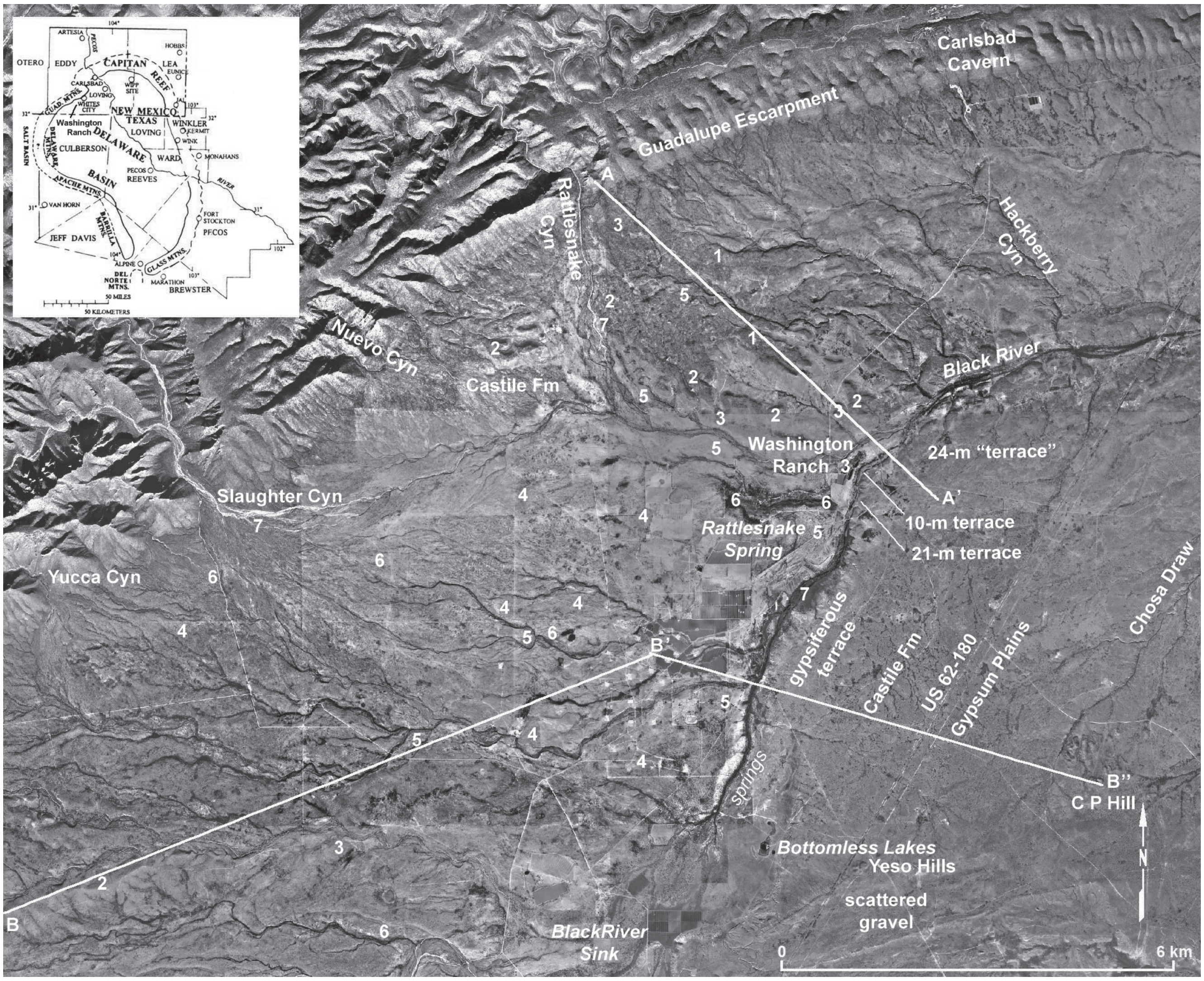

FIGURE 1. Digital orthophotograph of the area near Washington Ranch showing features named in text, lines for projected cross sections, terrace-levels east of the Black River, and numbered piedmont levels west of the Black River (1 being highest and oldest, 7 being lowest Holocene alluvium).

of displacement. The monocline is thought to have formed during the Laramide Orogeny by reactivation of the older Pennsylvanian thrust (Hayes, 1964).

The Castile Formation is about 520 m thick to the east in the Delaware Basin and consists of varves and larger evaporitic depositional cycles of anhydrite, calcite and halite (Kirkland, 2003). Near Washington Ranch all of the halite and most of the anhydrite are dissolved by shallow groundwater, with the remaining anhydrite converted to gypsum. Wells south and west of Washington Ranch encounter thin Castile Formation (90-100 m) whereas wells along the Gypsum Plain to the southeast encounter more than 240 m. The dissolution front apparently follows the course of the Black River and forms the abrupt scarp along the west side of the Yeso Hills.

Dissolution of Castile Formation (and other evaporite formations to the east) has taken place several times in the past (Lee, 1925; Olive, 1957; Bachman, 1980; Crawford, 1993; Powers and Holt, 1993; Hill, 1996). At Washington Ranch and along US 62-180, local exposures of deformed (inwardly tilted) fine-grained and conglomeratic karst fills underlie Quaternary gravel deposits. The fills probably range from Miocene to Pliocene and early Pleistocene in age.

QUATERNARY GEOMORPHOLOGY AND STRATIGRAPHY

Washington Ranch headquarters is at the junction between the Black River, the extensive alluvial fan from Slaughter Canyon to the southwest, and the composite drainage from Rattlesnake and Nuevo Canyons to the west and northwest (Fig. 1). Very poorly to well sorted Quaternary gravels are exposed at several different topographic levels and reflect a decipherable recent geologic history. Though wide-spread solution subsidence is suspected across the area, the various levels of gravel and geomorphic surfaces are fairly continuous and only locally deformed by sinkhole-style subsidence. Between the Guadalupe Escarpment and the Black River, gravel deposits and geomorphic surfaces are clearly piedmont alluvium. But closer to the Black River, these differing levels of gravel units raise questions about their origin and what geomorphic/depositional terms are applicable. Are the different levels of gravel to be called "terraces", implying transport and deposition by the Black River? Or are the gravel deposits "piedmont" alluvium, implying that they are "footslope deposits" derived from the Guadalupe Mountains, and therefore might be at different topographic levels on opposite sides of the present course of the Black River, and possibly graded to solution subsidence levels rather than to the river? The amount of solution subsidence beneath the course of the Black River affects not only the slope from the west, but also the interpretation of ages of the deposits.

The Quaternary gravels near Washington Ranch are composed of pebbles and cobbles of limestone derived from the Capitan Reef and near backreef units eroded from the Guadalupe Escarpment a few kilometers north and west of the ranch. Some of the gravels locally contain siliceous pebbles, originally recycled from Cretaceous conglomerates and probably recycled from Mio-Pliocene streams draining the Guadalupe uplift from the west (age equivalents of Ogallala and Gatuña Formations); these once covered the area but have been mostly removed by erosion (Hayes, 1964; Hawley 1993b; Powers and Holt, 1993; Hill, 1996).

Deposits of different ages are well cemented by calcium carbonate to form extremely durable limestone cobble conglomerates that break across clasts (Horberg, 1949; Sares, 1984). Both Horberg and Sares imply that the lowest exposed well cemented conglomerates are the oldest (except for remnants along the crest of the Yeso Hills to the southeast), but whether the oldest units are let down along the Black River, or whether more recent units are equally well cemented in more recently saturated environments remains to be determined. Different levels of conglomerates are exposed in prominent bluffs along the southeast bank of the Black River in stream banks. In places they armor the streambed at Washington Ranch. Upstream from the ranch, gully-bed cementation is currently forming new conglomeratic rock.

Other than the discontinous smattering of loose limestone gravel preserved in karst features of the Yeso Hills 60-65 m above the Black River, the highest relatively well-preserved geomorphic level of piedmont gravel descends from the Guadalupe Mountains toward the Black River north of Rattlesnake Canyon about 45 m above the present level of Rattlesnake drainage (Fig. 2). This level and the second level a few m inset below it have large numbers of karst features developed in them, particularly near the mountain front, and they are discontinuous to the Black River. Arbitrary and probably unwarranted straight-line projections of the tops of either of these two levels could possibly grade to a more continuous, nearly planar level of gravel (conglomerate) on the east side of the Black River above Washington Ranch at 1,113 m (3,650 ft) elevation, 24 m above the Black River. Questions remain as to whether the gravel east of the Black River and continuing northeast downstream from US 62-180 is part of this old piedmont alluvial slope, or whether it is a later river terrace. This level appears not to have an equivalent paired terrace on the northeast side of the Black River downstream from Washington Ranch, where southeast-sloping piedmont surfaces predominate. Other piedmont levels between Rattlesnake Canyon and Hackberry Canyon north of the Black River are complicated and not yet investigated. The high-level, nearly continuous conglomerate on the east side of the Black River apparently is not present south of Washington Ranch. Dissolution features parallel its southern edge.

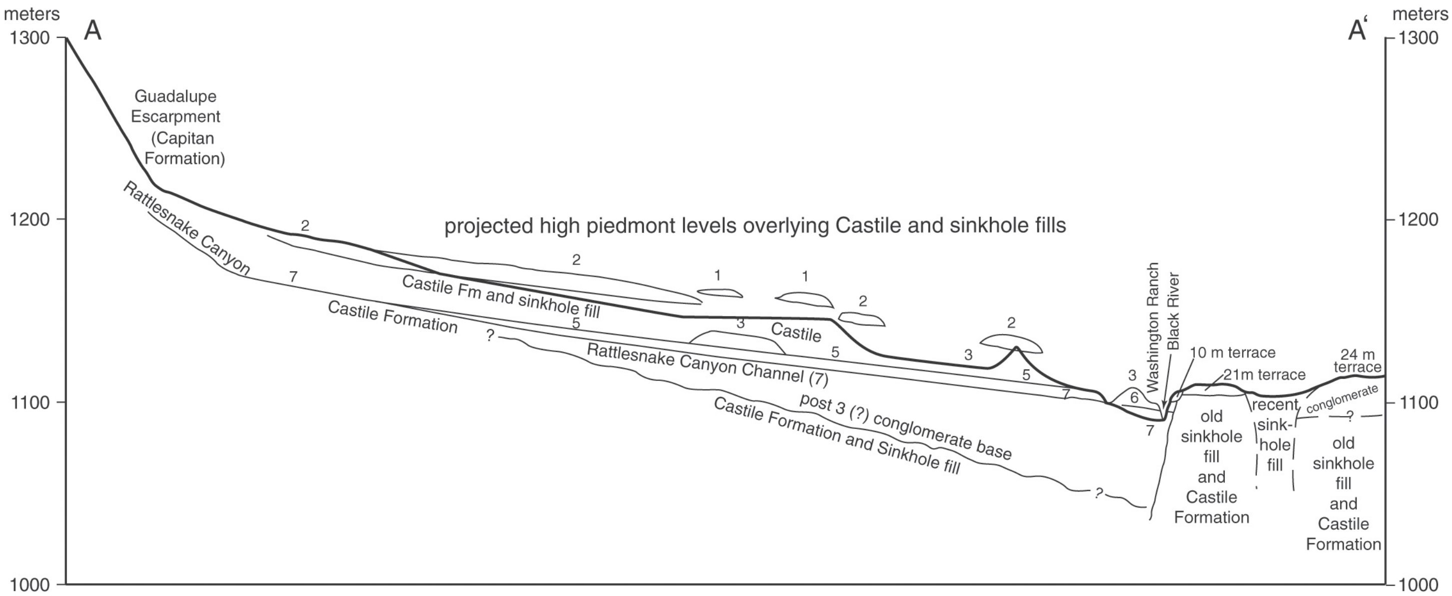

FIGURE 2. Projected cross section A-A' (10 x vertical exaggeration) showing piedmont levels northeast of Washington Ranch, subsurface conglomerate, karst fill, and Castile Formation, and terrace levels southeast of Washington Ranch.

Piedmont level three is inset below the two higher levels and preserved south of Slaughter Canyon (also presumably southwestward to McKittrick Canyon) and near the mouth of Rattlesnake Canyon (Fig. 2 and 3). Level three is 10 m above Rattlesnake drainage and up to 13 m above Slaughter Canyon drainage. It is dissected, discontinuous, and has circular- to-ovoid karst features.

On the east side of the Black River at Washington Ranch below the 24-m level "terrace" (?) mentioned above, gravel terraces are 20-21, and 7-10 m above the present river. The upper level is well cemented, 3-5 m thick and has a well-developed stage IV petrocalcic soil at the top. It overlies karst fill and is deformed by later subsidence. This level is truly a terrace, with a paired level to the northeast on the opposite side of the Black River valley. This terrace may correlate to piedmont surface three west of the Black River. The lower level of terrace seen at Washington Ranch with a top 10 m above the river is less cemented, and exhibits a mixture of crossbedded pebbly sand and fine-grained alluvium. Neither of these two east-side terraces is seen much farther south than the Black River road crossing southeast of Washington Ranch. This suggests the possibility of extensive solution subsidence of former terraces to the south. Perhaps the reason that these two terraces are preserved at Washington Ranch is because they rest on older karst fill and cannot subside farther.

Piedmont gravel levels four, five, and six west of the Black River are all inset below the higher piedmont and terrace levels on both sides of the river. They are preserved from south of Slaughter Canyon (and presumably southwestward to McKittrick Canyon) to Rattlesnake Canyon, and are all related to modern canyon-mouth drainages. All have circular- to- ovoid karst features affecting their surfaces, but higher (and presumably older) levels appear to have nearly equivalent numbers of sinkholes. Level four is 6-9 m above Rattlesnake drainage and up to 11 m above Slaughter Canyon drainage. Levels four, five, and six are closely spaced, particularly at their distal ends near the Black River, but are recognizable at Washington Ranch. Level 6 is only 4-5 m above present channels (level 7). The main problem with distinguishing these piedmont-slope levels is that very little is known about their thicknesses and possible inset relationships in the subsurface. This leads to basic questions about the age of well-cemented conglomeratic deposits seen underneath a gypsiferous terrace at the Black River springs near Bottomless Lakes (see below) and Holocene alluvium and marsh deposits along the Black River. Well records west of the Black River near Rattlesnake Springs indicate 11-36 m of conglomerate overlying finer-grained (karst?) fill (Bowen, 1998; Bureau well records) and more than 100 m of alluvium on the medial piedmont (Bowen, 1998). Farther south, a well spudded on level five encountered 57 m of conglomerate above Castile Formation. The thicknesses of distal piedmont (taken as a group) and the proximity of the sharp western edge Castile Formation of the Yeso Hills to the east suggests that these deposits have subsided and graded toward the Black River as dissolution took place beneath both the river and distal fan(s). The surface of the fan has recorded cuts, fills, and circular karst features only partially dependent on subsurface subsidence.

Just upstream from Washington Ranch on both sides of the Black River are remnant to continuous exposures of a fine-grained, extremely gypsiferous "terrace" fill, at least 7 to 13 m thick and about that far above the river. Locally it overlies well-cemented conglomerate equivalent in elevation to piedmont-surface level 5. At its downstream end on the east side of the Black River, it approaches the level of the 21-m conglomeratic terrace. The unit is cut by spring sapping, meanders of the modern Black River and tributaries from the west, and has developed karst features at Bottomless Lakes. The origin of this unit remains in question and perhaps should not be called a terrace because it may not be fluvial in origin. Sares (1984) suggested that it (or a similar unit in Chosa Draw) is eolian, and presented a granulometric sand-sized distribution. Along the Black River, some of this unit might be eolian, part of it might be piedmont-slope deposits from the Yeso-Hills Castile dissolution scarp to the east, and some of it appears to have been deposited by gypsum- and carbonate-depositing springs because there is snail-bearing spring tufa overlying it locally. Clearly this unit reflects an episode of landscape stability and non-clastic deposition in this reach of the Black River. It appears to be late Quaternary in age and may have formed after sinkholes captured the Black River and other major drainages upstream. Its relationship to the southern ends of terraces at Washington Ranch remains to be examined closely, but their topographic level may have controlled the amount of aggradation of fine-grained deposits upstream.

Tufa

The most visually striking surface features at Washington Ranch headquarters are the extensive tufa deposits that line the

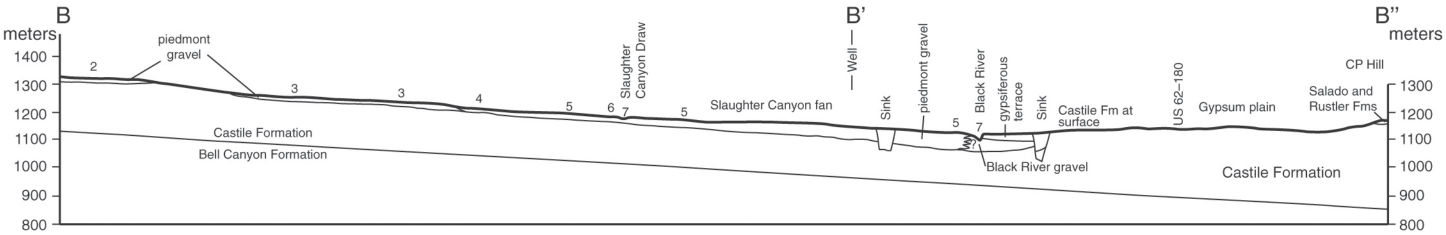

FIGURE 3. Projected cross section B-B'-B" (4 x vertical exaggeration) showing piedmont levels, Slaughter Canyon fan, karst features, gypsiferous "terrace" or "footslope", and thicker Castile Formation east of the Black River.

Black River and form tufa dams at a minimum of five locations. The most accessible tufa dam is formed just west of the Black River crossing. Casts of reeds and other aquatic plants are some of the more common features seen in the tufa deposits. Multiple episodes of tufa genesis ("tufafication," a term coined by L. Land in 2006) are indicated along this reach of the Black River. Superposition of the gravels and marsh deposits suggests that some of the dams are older, previously buried features that were exhumed by later stream erosion. Later episodes of tufa formation are indicated by tufaceous material cementing and overlying Quaternary gravel, and more recently, interbedded with snail-bearing Holocene alluvium. In at least two places along the Black River tufa has "dripped" vertically down 3-4 m free faces (open to air) developed on well cemented conglomeratic units. This implies that the Black River had cut a deeper trench through the conglomerate and water had seeped from the canyon sides to deposit the tufa. The free-face tufa south (upstream) of the middle tufa dam faces east and the free-face tufa north of the same dam faces west, suggesting that the water seeped from opposite sides of the inner canyon and that the middle tufa dam across the inner canyon developed after the free-face tufa had formed. The free-face tufa and most extensive tufa dam in between are all aligned along a 15 degrees northeast trend. At the upstream end, conglomerate rests on tufa at the level of piedmont deposit 6, implying that gravel was transported at that level after the tufa was deposited, and that the bulk of the tufa predates piedmont level 6. However, this would imply filling of the free-face canyon with coarse-grained alluvium and we have not seen evidence for this.

Holocene Alluvium

Tufa deposits and conglomerate along the streambed of the Black River are overlain by ~2 m of gray silty sediment with abundant snail shells, which are late Holocene marsh and floodplain deposits (level 7). The fine-grained Holocene deposits must have filled the former incised tufa-lined channel, but these deposits have been excavated by historic floods along the Black River and by humans to create intermittent ponds at Washington Ranch headquarters. Downstream from Washington Ranch these fossiliferous deposits interfinger with thin beds of calcium-carbonate tufa deposits.

Hydrology

The low-lying composite Quaternary gravel/conglomerate unit is an important local aquifer, providing water supply for Washington Ranch and local ranchers in the Black River valley. Recharge occurs in the upper reaches of the alluvial fan at the mouth of Slaughter Canyon (Hill, 1996). Gravels contained in the fan are hydraulically disconnected from the adjacent Capitan Reef aquifer, within which water levels are over 100 m lower than in the conglomerate aquifer (Sares, 1984; Hill, 1996). Groundwater flows down-gradient in part through karstic solution conduits developed within the carbonate-cemented conglomerate, with discharge from springs or directly into the Black River as baseflow (Bowen, 1998).

The largest spring in the area, Rattlesnake Springs, located ~1.6 km SW of the Ranch, flows at rates up to 7,200 liters/min from the conglomerate aquifer. The water from the springs is of good quality, with TDS of ~450 mg/l, and is pumped to the top of the reef escarpment to provide water for the Carlsbad Caverns National Park visitors center (Hill, 1996). Water from Rattl esnake Springs is also carried by irrigation ditches to Washington Ranch, where it fills the three impoundments on the facility. The spring currently provides ~3.8 million liters/day to the Ranch, but during droughts that volume may drop as low as 200,000 liters/day. Washington Ranch also has a 12 m deep domestic water supply well at Rattlesnake Springs with artesian flow.

In contrast, water at the Cottonwood Day Use Area upstream along the Black River and at Bottomless Lakes is sulfate-rich (highly gypsiferous). The Black River springs and Bottomless Lakes are probably fed by discharge from an alluvial aquifer composed of clastic gypsum, or gypsite, derived from the Castile Formation. TDS concentrations of ~1338 mg/l have been measured at the Black River springs.

CONCLUSIONS

Late Neogene geologic history near Washington Ranch is shown by several levels of piedmont slopes and river terraces that are affected by both local and regional solution subsidence of the underlying evaporitic Castile Formation. Seven piedmont levels ranging from highest remnants to modern tributary channels reflect changing base levels from the Guadalupe Escarpment toward the Black River and beyond. Older high piedmont levels west and northwest of the Black River cap outcrops of Castile Formation, whereas younger piedmont levels are graded close to the level modern tributaries and the Black River. The underlying Castile Formation is thinned markedly by solution and up to 100 m of coarse alluvium underlie the younger piedmont deposits, reflecting long-term subsidence of the distal parts of the piedmont and Black River. Ovoid karst features cut the piedmont deposits at all levels. Two types of terraces are preserved along the Black River in the vicinity of Washington Ranch-- fluvial gravel terraces, and a fine-grained gypsiferous "terrace" that may indicate an episode of no clastic transport along the river. Holocene and late Pleistocene alluvium, marsh, and tufa deposits mark the current river level, but some of the tufa occupies an older buried paleochannel with vertical banks that was later buried by Holocene alluvium. Differences in water chemistry in springs and sinkholes reflect different aquifers including the carbonate-rich piedmont gravel aquifer of Rattlesnake Spring and the gypsic aquifer of Bottomless Lakes.

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