The Santa Fe Group in the northern Winston graben, southwest New Mexico, and how changing Rio Grande rift tectonism may have influenced its deposition and erosion

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THE SANTA FE GROUP IN THE NORTHERN WINSTON GRABEN, SOUTHWEST NEW MEXICO, AND HOW CHANGING RIO GRANDE RIFT TECTONISM MAY HAVE INFLUENCED ITS DEPOSITION AND EROSION

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Abstract—The northern Winston graben of the Rio Grande rift, located 55-85 km northwest of Truth or Consequences, NM, is asymmetrically tilted westward towards the Black Range fault. This fault and the west-down Red Paint Canyon fault zone along the eastern side of the basin were primarily active in the Miocene, with probable waning activity in the Pliocene and minimal movement in the Quaternary. Fourteen stratigraphic sections and ~200 outcrop descriptions indicate that piedmont facies dominate the Santa Fe Group in the northern Winston graben, with clayey playa facies located west-northwest of the Monticello Box. Although there was a relatively major stream flowing into the playa from the north, there is no evidence it extended into the San Augustin Plains. The upper Santa Fe Group is generally weakly cemented and dips 0-15° west. Its piedmont sediment is differentiated into a proximal-medial, coarser-grained facies and a distal, finer-grained facies. The latter grades laterally into the clayey playa facies. The upper Santa Fe Group unit is interpreted to be middle(?) to late Miocene (possibly earliest Pliocene) in age because it is contiguous with slightly tilted basin-fill strata to the south capped by a 4.9 Ma basalt flow. The middle Santa Fe Group is assigned to steeply tilted (>15° dips) and moderately-strongly cemented strata. Early Miocene in age, the middle unit is locally exposed on the footwall of the Red Paint Canyon fault zone (probably in paleovalleys) and at Ojo Caliente warm springs. The oldest late Cenozoic sedimentary units consist of well-cemented, tuffaceous volcaniclastic sediment of the Beartrap Canyon Formation and unit of East Red Canyon; these are age-equivalent with the lower Santa Fe Group unit in the southern Winston graben. Both paleocurrent data and the spatial distribution of the aforementioned facies indicate a closed basin in the middle(?) to late Miocene, and possibly earliest Pliocene. Tectonic tilt rates are interpreted to have slowed in the latest Miocene and Pliocene, consistent with low dip magnitudes in the upper Santa Fe Group unit. During this decrease of tilt rates, presumably accompanied by a decrease in basin subsidence rates, paleosols developed in the distal piedmont facies and locally the western piedmont prograded eastward over the playa facies. Low subsidence rates probably facilitated spill-over and the transition from a closed to open basin. Latest Miocene-earliest Pliocene pediments along the margins of the basin were onlapped by thin (5-10 m, locally as much as 35 m) upper Santa Fe Group deposits. Widespread erosion of the Santa Fe Group in the Pliocene produced relatively flat, extensive surfaces in the Winston graben, concomitant with >100-130 m of aggradation in the Engle and Palomas basins to the east. A shift of tectonic strain towards the center of the rift likely accounts for this spatial contrast in erosion/deposition.

INTRODUCTION

The Winston graben of the Rio Grande rift is 65 km long and 10-17 km wide. This paper describes the structural setting, Santa Fe Group (SFG) stratigraphy and sedimentation, and subsequent Pliocene erosion of the northern half of this graben. Particular emphasis is placed on description and the spatial distribution of their facies. After presenting new descriptive and paleocurrent data, this paper discusses the role Mio-Pliocene tectonic activity played in the facies distribution of the upper SFG, the transition from a closed basin to an externally drained basin, and the development of pediments and other erosion surfaces here during a time aggradation continued in the central part of the rift.

GEOGRAPHIC SETTING

The northern Winston graben is located about 55-85 km northwest of Truth or Consequences, New Mexico, and is separated from the southern Winston graben by a low drainage divide 14 km north of the town of Winston (Fig. 1). Note that the southern Winston graben is defined differently in this paper than by Cikoski and Harrison (2012). In the northern Winston graben, I studied the SFG in the Alamosa Creek drainage upstream of the Monticello Box, a ~130 m-deep gorge cut in Oligocene volcanic rocks (Fig. 1). Major tributaries of Alamosa Creek are labeled on Figure 1. The Black Range lies west of the studied area, and the San Mateo Mountains lie to the east. Immediately upstream of the Monticello Box are the Ojo Caliente warm springs (Fig. 1). Pleistocene incision along Alamosa Creek and adjoining tributaries has produced relatively narrow, 50-90 m deep valleys between dissected mesas covered by pinon-juniper forest.

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STRUCTURE OF THE WINSTON GRABEN

The northern Winston graben is bounded on the west and east by two major normal fault zones and has been interpreted as a symmetric graben (Harrison, 1992, 1994). However, strata between the faults generally dip westward and there is a much steeper gravity gradient along the western margin fault than on the east side of the basin (Fig. 2; Gilmer et al., 1986), indicating more throw along the western margin fault and a west-tilted, asymmetric geometry. Called the Black Range fault by Cikoski and Harrison (2012), the western margin fault separates thick SFG to the east from thin SFG and Oligocene volcanic rocks to the west, and is demarcated by eroded fault scarps up to 10-15 m high.

The eastern basin-margin fault zone consists of several west-down, and lesser east-down, fault strands within a 4 km-wide zone. It represents a northward continuation of the Red Paint

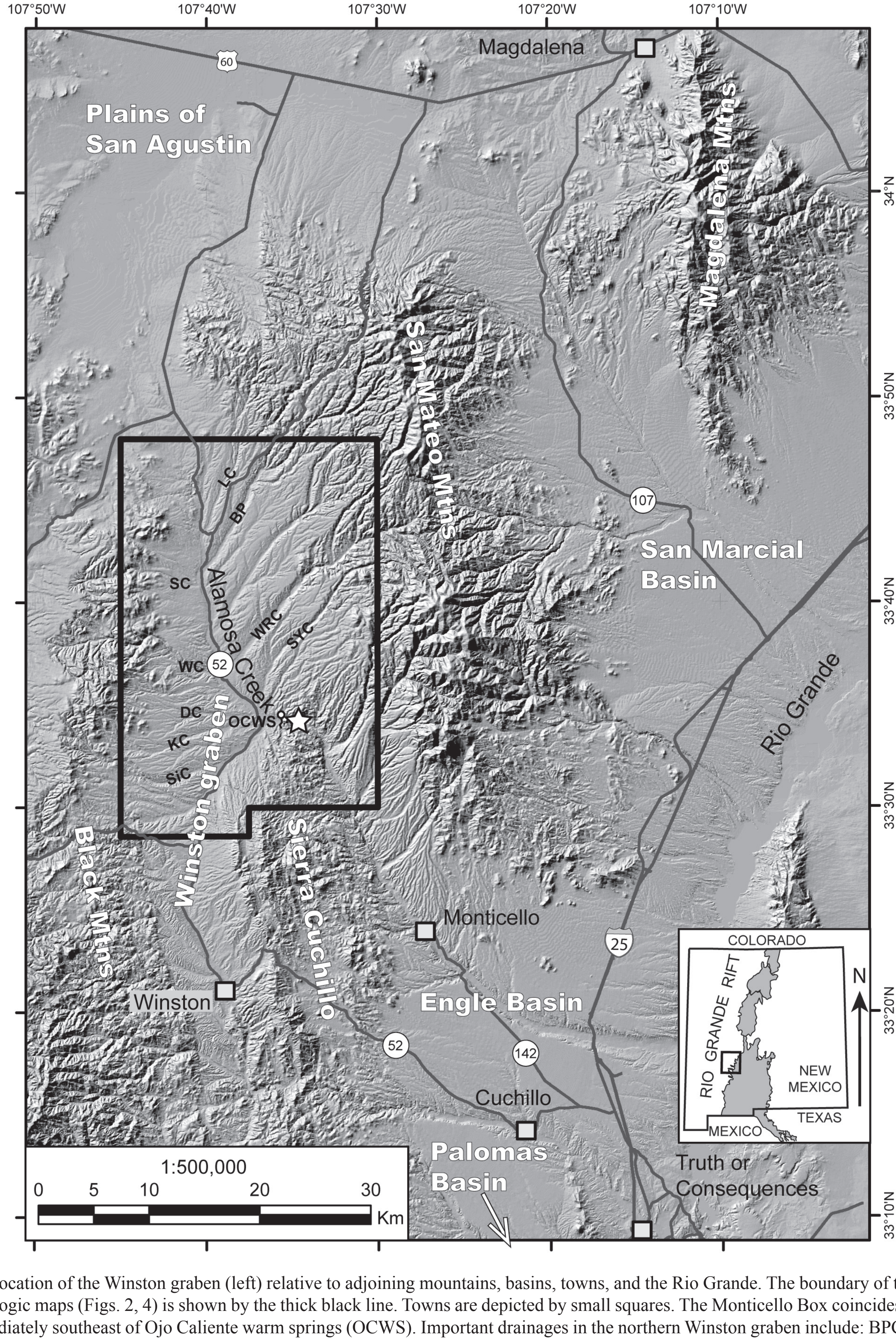


FIGURE 1. Location of the Winston graben (left) relative to adjoining mountains, basins, towns, and the Rio Grande. The boundary of the larger scale fault and geologic maps (Figs. 2, 4) is shown by the thick black line. Towns are depicted by small squares. The Monticello Box coincides with the plotted star immediately southeast of Ojo Caliente warm springs (OCWS). Important drainages in the northern Winston graben include: BPC = Big Pigeon Canyon, DC = Duck Canyon, KC = Knisely Canyon, LC = Limestone Canyon, SC = Stone Canyon, SiC = Silver Creek, SYC = Sim Yaten Canyon, WC = Wahoo Canyon, WRC = West Red Canyon.

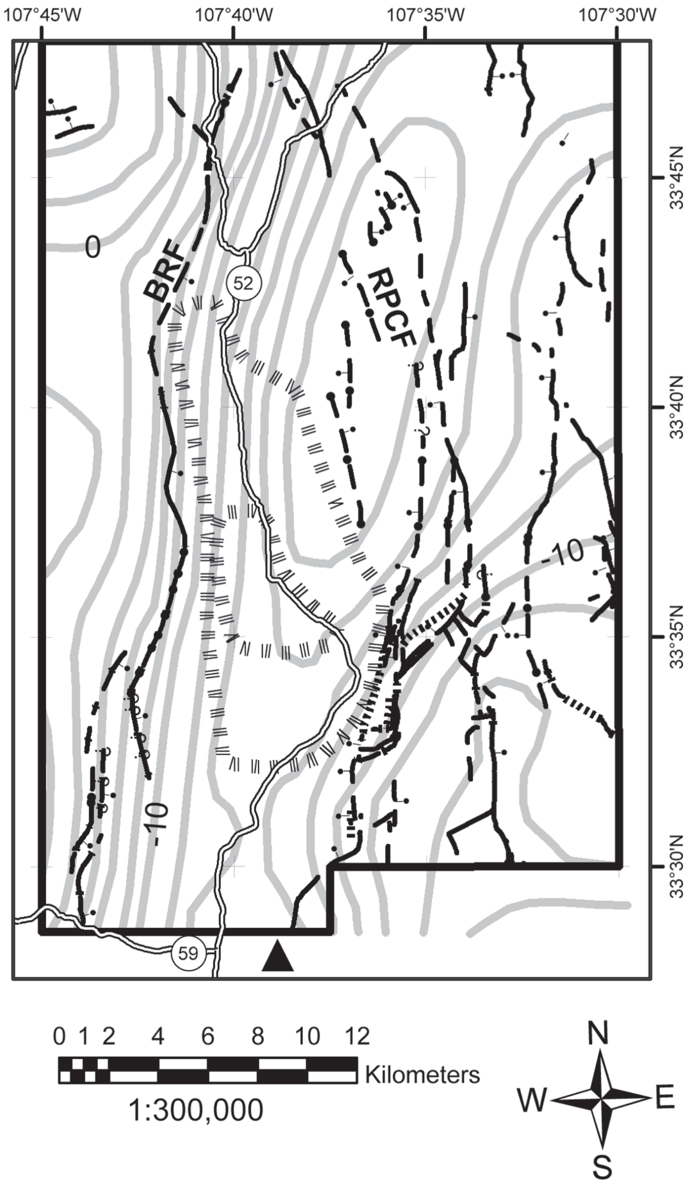


FIGURE 2. Faults plotted on a residual-gravity-anomaly map of the northern Winston graben. The latter was constructed by subtracting a third-order best-fit polynomial surface of the regional gravity gradient from corresponding Bouguer gravity values (Gilmer et al., 1986). Gravity contours are in milligals. The black boundary coincides with that of the geologic map (Fig. 4). BRF = Black Range fault zone and RPCF = Red Paint Canyon fault zone. Hatched pattern denotes the approximate facies boundaries of Figure 4. Note the steep gravity gradient along the Black Range fault. This gradient and the westerly dips over much of the basin support the interpretation of an asymmetric, west-tilted graben. The low gravity values in the northeast part of the map are probably due to the Mt Withington and Beartrap cauldrons. Exploratory boreholes that indicate as much as 660 m of clastic basin-fill thickness are collectively shown by the black triangle along the southern boundary (Harrison, 1992, p. 269, and pers commun. cited therein).

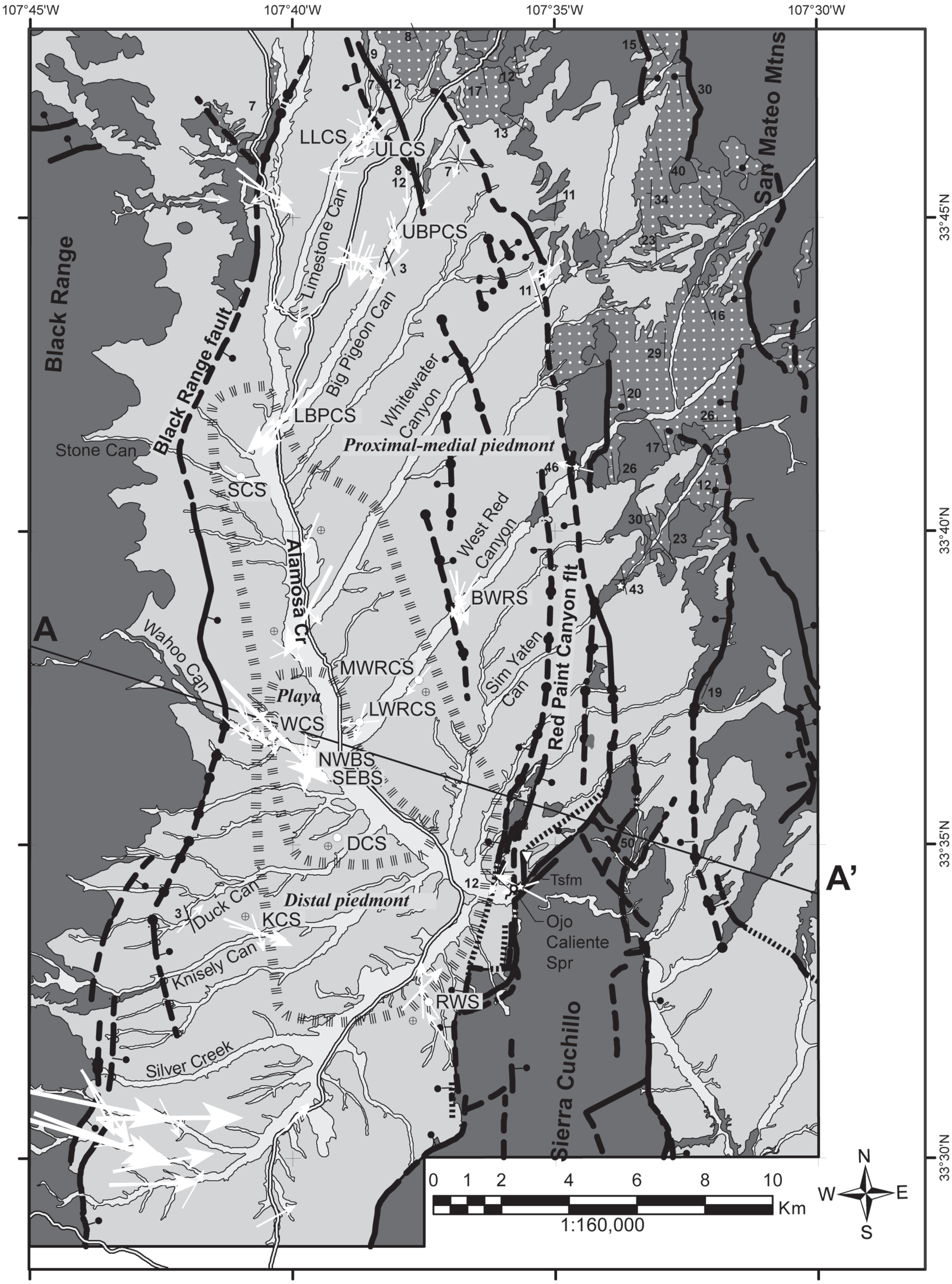
Canyon fault zone of McLemore (2010), and I apply this name to the entire eastern basin-margin fault zone. The longest fault strand is up to 26 km long, west-down, and demarcated by degraded fault scarps up to 10-15 m high and changes in SFG thicknesses (Fig. 3). In the Monticello Box area, the westernmost fault strand in this zone (about 15 km long and west-down) is located 0.8-0.9 km west of the Ojo Caliente warm springs and continues northward to West Red Canyon (Fig. 4A). In the Monticello Box area, McLemore (2010) mapped several short faults (1-3 km long) and volcanic bedrock (mostly Turkey Springs Tuff) between the aforementioned 26 km- and 15 km-long fault strands (Fig. 4). The coincidence of this faulted terrain with warm and cold springs, including the Ojo Caliente warm springs, as well as localized, older Neogene hydrothermal alteration, suggests these faults play an important role in the upwelling of ground water (McLemore, 2010).

Sparse gravity data and exploratory well drilling provide insight into the structural geometry of the northern Winston graben. In addition to supporting a west-tilted, asymmetric geometry, as noted above, contouring of gravity data (Gilmer et al., 1986) suggests a structural high at the southern end of the basin, ~2 km north of the modern drainage divide (Fig. 2, 33° 30-31' N latitude and 107° 40' W longitude). This high coincides with a right-lateral stepping of the basin-margin faults and may reflect an early(?) fault segment boundary. Exploratory well drilling near the southern drainage divide of Alamosa Creek (Fig. 2) indicates that clastic basin-fill overlying Oligocene volcanic rocks is as much as 660 m thick (Harrison, 1992, p. 269, and pers. commun. cited therein). Based on the relative positions of gravity contours relative to this well (Fig. 2), I estimate a total basin-fill thickness of about 1000 m for the deepest part of the northern Winston graben.

OLIGOCENE VOLCANIC ROCKS

Volcanism and cauldron-forming eruptions related to the Mogollon-Datil volcanic field formed the volcanic rocks underlying SFG sediment in the Winston graben. These rocks also constitute the bulk of the Black Range and San Mateo Mountains.

FIGURE 3. Fault scarp along the longest strand of the Red Paint Canyon fault zone, 1-2 km southeast of West Red Canyon. View to the east, with the southern San Mateo Mountains in the background. Arrows point to the base of this 10-15 m-tall scarp.


107°45'W
107°40'W
107°35'W
107°30'W
33°45'N
33°40'N
33°35'N
33°30'N
Black Range
Black Range fault
San Mateo Mtns
LLCS
ULCS
UBPCS
Limestone Can
Big Pigeon Can
Whitewater Canyon
LBPCS
Proximal-medial piedmont
Stone Can
SCS
West Red Canyon
BWRS
Alamosa Cr
Red Paint Canyon flt
Sim Yaten Can
A
A'
Wahoo Can
MWRCS
Playa
WCS
LWRCS
NWBS
SEBS
DCS
Tsfm
Ojo Caliente Spr
Distal piedmont
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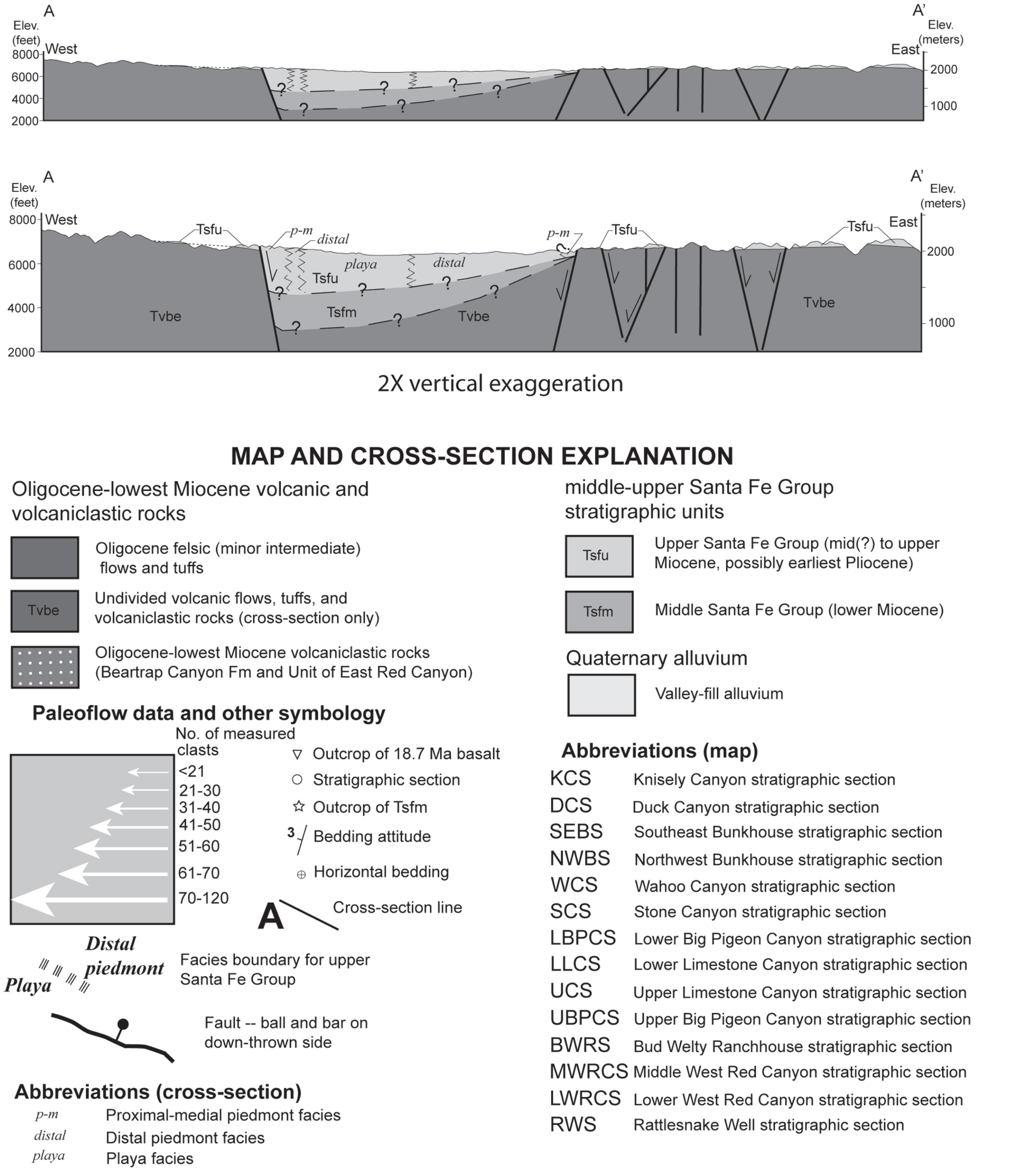

FIGURE 4. A) Geologic map of the northern Winston graben (left page), showing five compiled geologic units, faults, paleocurrent data, and locations of stratigraphic sections. Cross section A-A' is located immediately north of Monticello Box and the Ojo Caliente warm springs. Compiled from maps of Ferguson et al. (2007), Osburn and Ferguson, (2007, 2010), McCraw (2003a, b), and McLemore (2010). Location of Black Range fault is interpreted from my observations in the field. Some strands of the Red Paint Canyon fault were modified from Ferguson et al. (2007). Paleocurrents are plotted as average azimuths from Appendix 3. B) Cross-section A-A' (above), the lower one being vertically exaggerated, and explanation for the geologic map. Note that facies are only differentiated for the upper Santa Fe Group.

Following a period of andesitic volcanism, preserved in the Black Range, a period of largely silicic volcanism occurred in four major pulses between 36 and 24 Ma (McIntosh et al., 1992). In the San Mateo Mountains, this silicic volcanism produced three notable cauldrons and associated ignimbrites: the Nogal Canyon cauldron and Vicks Peak Tuff (28.4 Ma), the Mount Withington cauldron and South Canyon Tuff (27.4 Ma), and the Beartrap cauldron and Turkey Springs Tuff (24.3 Ma) (Deal and Rhodes, 1976; Chapin et al., 1978; Elston, 1989; Chapin, 1978, 1989; McIntosh, 1989; McIntosh et al., 1992; Chapin et al., 2004). The unit of East Red Canyon and the Beartrap Canyon Formation -- both consisting largely of volcaniclastic pebbly sandstone, sandstone, and conglomerate -- filled the Mt. Withington and Beartrap cauldrons, respectively, and are common along the eastern and northern sides of the Winston graben (Fig. 4; Ferguson et al., 2007; Osburn and Ferguson, 2007). The Beartrap Canyon Formation also contains rhyolite domes and flows. Because it underlies the middle SFG unit, Beartrap Canyon Formation sediment is described below. In the northern Black Range, several rhyolite domes were formed between 29.0 and 28.1 Ma (McIntosh et al., 1992).

SANTA FE GROUP PREVIOUS WORK AND NOMENCLATURE

Santa Fe Group basin fill in the Winston graben has received less attention by geologists than the aforementioned volcanic rocks. Richard Harrison mapped the southern Winston graben and described basin-fill strata there as consisting of conglomerate, sandstone, mudstone, and minor volcanic ash beds (Harrison, 1989, 1992). Basin-fill in the southern Winston graben has been informally referred to as “Winston beds” by Jahns (1955a) and Chapin et al. (1978), but subsequent workers have generally refrained from using that term. The southern Winston graben has been recently remapped, with particular emphasis on the SFG (see Cikoski and Harrison, 2012).

Santa Fe Group deposits to the east, in the Engle and Palomas basins, have been studied by numerous workers (Gordon, 1910; Harley, 1934; Heyl et al., 1983; Jahns, 1955a, b; Kottlowski, 1955; Maxwell and Oakman, 1986; Lozinsky, 1985; Lozinsky and Hawley, 1986). An upper interval of the SFG, consisting of relatively narrow axial river facies interfingering with piedmont facies to the west and east, is formally called the Palomas Formation and is as old as early Pliocene (Lozinsky and Hawley, 1986). Aggradation of the Palomas Formation continued until 780 ka (Seager and Mack, 2003). In the Engle Basin, major streams incised into the constructional surface of the Palomas Formation after 780 ka. I infer this middle to late Pleistocene incision extended into the Winston graben.

I extend the SFG terminology of Cikoski and Harrison (2012) to the northern Winston graben, except for their lower SFG unit (Fig. 5). In the southern Winston graben, a package of tuffaceous conglomerate and sandstone overlies an angular unconformity developed on top of the tuff of Little Mineral Creek, stratigraphically below the Vicks Peaks Tuff. Cikoski and Harrison (2012) argue that this unconformity represents early tilting associated

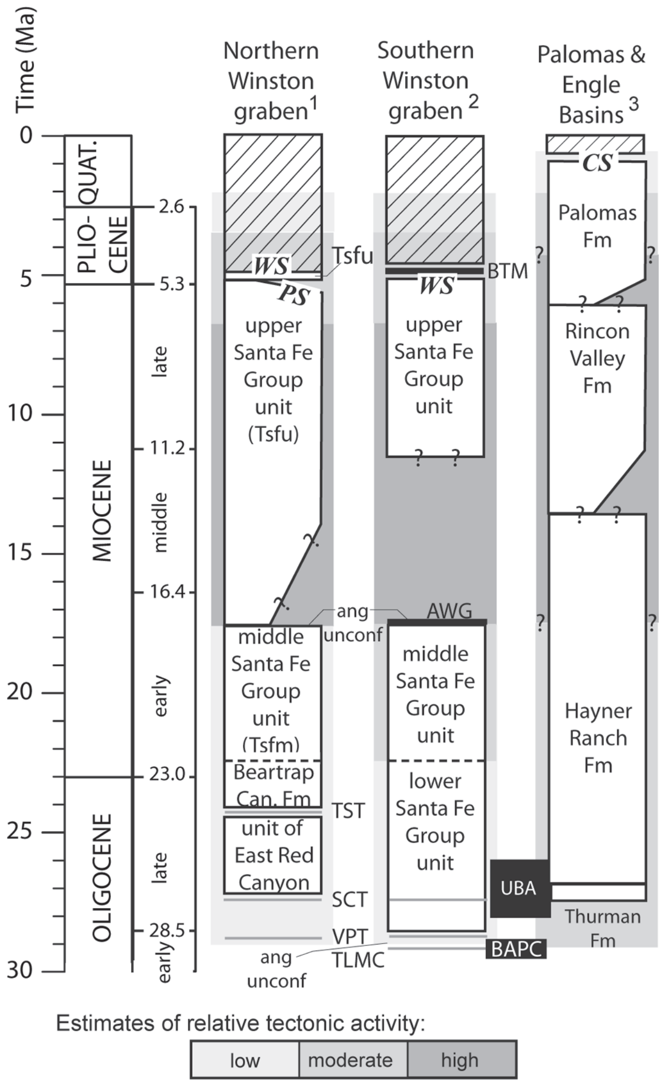

FIGURE 5. Diagram showing age control and stratigraphic correlations between the northern and southern Winston graben, as well as the Palomas and Engle Basins to the southeast. Lavas (black lines and rectangles) are abbreviated as follows: BTM = Basalt of Tabletop Mesa; AWG = Andesite of Winston graben; UBA = Uva basaltic andesite; BAPC = Basaltic andesite of Poverty Creek (Cikoski and Harrison, 2012; Mack, 2004). Tephras (dark gray lines) are abbreviated as follows: TST = Turkey Springs Tuff; SCT = South Canyon Tuff; VPT = Vicks Peak Tuff; TLMC = Tuff of Little Mineral Creek. Age control for these tuffs is from McIntosh et al. (1991). Surfaces are abbreviated as: WS = Winston surface; PS = pediment surface on footwalls of basin-margin faults in northern Winston graben; CS = Cuchillo surface. Boxes filled by diagonal lines indicate Plio-Pleistocene erosion. Gray shades behind the stratigraphic boxes denote qualitative estimates of relative tectonic activity. These estimates are based on: 1) this work; 2) Cikoski and Harrison (2012); and 3) Lozinsky (1985), Seager and Mack (2003), and Mack (2004).

with the Rio Grande rift, and therefore assign the overlying tuffaceous strata to the lower SFG (using the SFG definition of Hawley et al., 1969). The Beartrap Canyon Formation and unit of East Red Canyon both overlie the Vicks Peak Tuff. This observation and the ages of the Turkey Spring and South Canyon tuffs indicate that these units correlate chronologically to the lower SFG unit (Fig. 5), even though past workers have not included them in the Santa Fe Group.

DATA

New data collected in this study include bedding attitudes, stratigraphic sections, and paleocurrent measurements. Bedding attitudes are plotted on the geologic map of Figure 4A. These generally dip to the west, but the youngest SFG strata are subhorizontal near Alamosa Creek. Stratigraphic sections are presented in Appendices 1 and 2, and their locations are shown on Figure 4A. A west-east stratigraphic fence diagram illustrates five of these sections and the lateral positions of upper SFG facies (Fig. 6). Appendix 3 is an Excel spreadsheet that tabulates the paleocurrent data, which were generally calculated from 2330 imbricated clasts (3-116 measurements per bed, median of 16). I did not correct for stratal tilts because of the low dips (less than 15°) in the upper SFG unit, and the orthogonal direction of imbrication relative to strike in the more steeply tilted middle SFG unit. Paleoflow data are relatively consistent within a given area of the northern Winston graben. In the west-northwest and northeast parts of the basin, paleoflow was to the southeast and southwest, respectively. Paleoflow was generally to the east in the southwestern part of the basin, to the north-northwest in the southeastern part, and to the southwest in the eastern part of the basin (Fig. 4A).

YOUNGEST CALDERA-RELATED STRATA

Beartrap Canyon Formation

The Beartrap Canyon Formation consists of volcaniclastic sandstone and conglomerate interbedded with rhyolitic flows, domes, and felsic non-welded tuffs (Deal and Rhodes, 1976; Ferguson et al., 2007; Osburn and Ferguson, 2007, 2010). The conglomerate contains pebble- to boulder-size clasts composed of rhyolite, welded tuff, and non-welded tuff. The sandstone, pebbly sandstone, and conglomerate are generally in medium to thick, tabular beds that are matrix- or clast-supported (Fig. 7). The gravel is subangular to subrounded and moderately to poorly sorted. Sandstone is commonly composed of fine- to very coarse, subrounded to subangular grains and in hand lens appears to contain >10% silt-clay. The Beartrap Canyon Formation is generally strongly cemented by (silica and clay) and a ledge former. Much of the formation appears to have been deposited by debris flows or hyperconcentrated flows (Fig. 7). Within the Beartrap Canyon Formation are various rhyolite lavas and lava domes (Ferguson et al., 2007; Osburn and Ferguson, 2007, 2010), which are locally jointed. In the north, Osburn and Ferguson (2010) mapped dacite in the Beartrap Canyon Formation.

The sedimentary rocks of the Beartrap Canyon Formation are similar to those of the unit of East Red Canyon, which filled the Mt. Withington cauldron and overlies the South Canyon Tuff, but

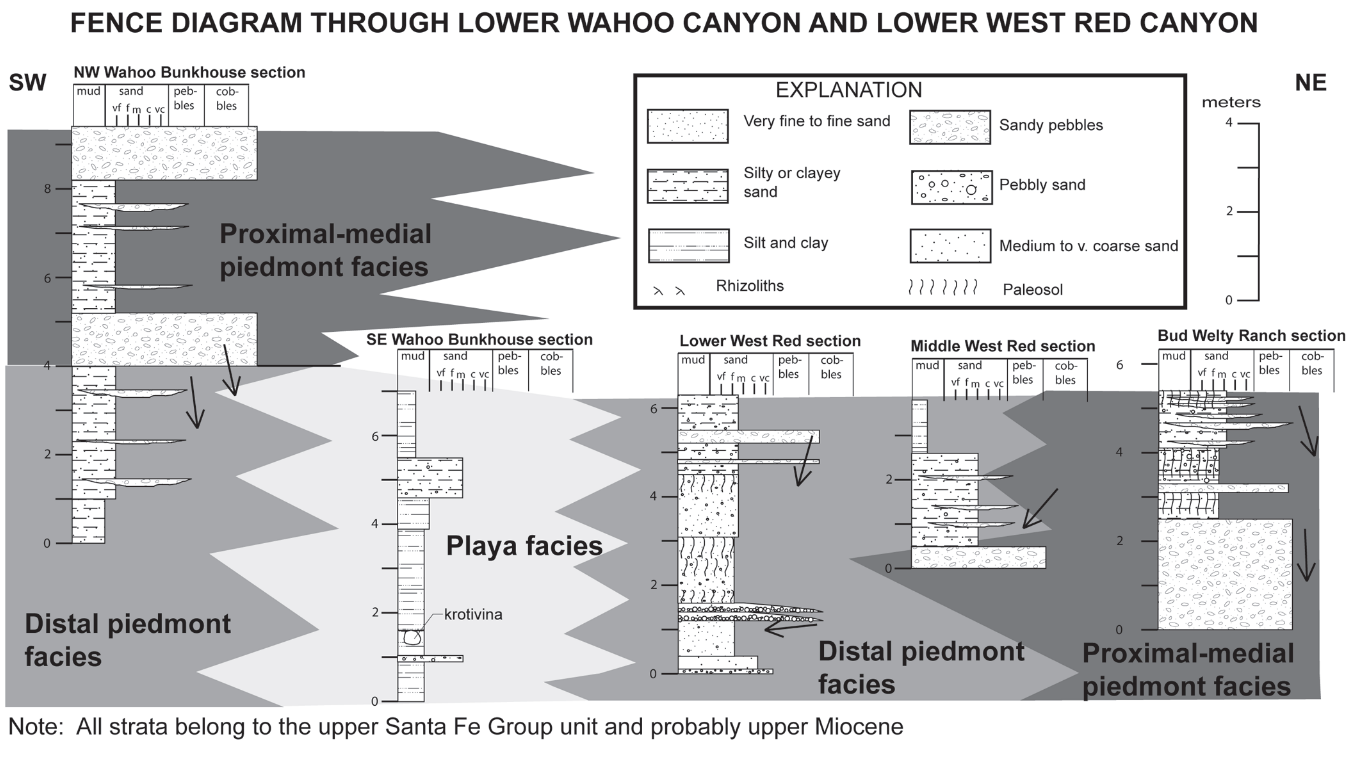

FIGURE 6. West-east stratigraphic fence diagram through lower Wahoo and lower West Red Canyons, illustrating the lateral positions of proximal-medial, distal, and playa facies of the upper Santa Fe Group. Figure 4A shows the locations of these stratigraphic sections.

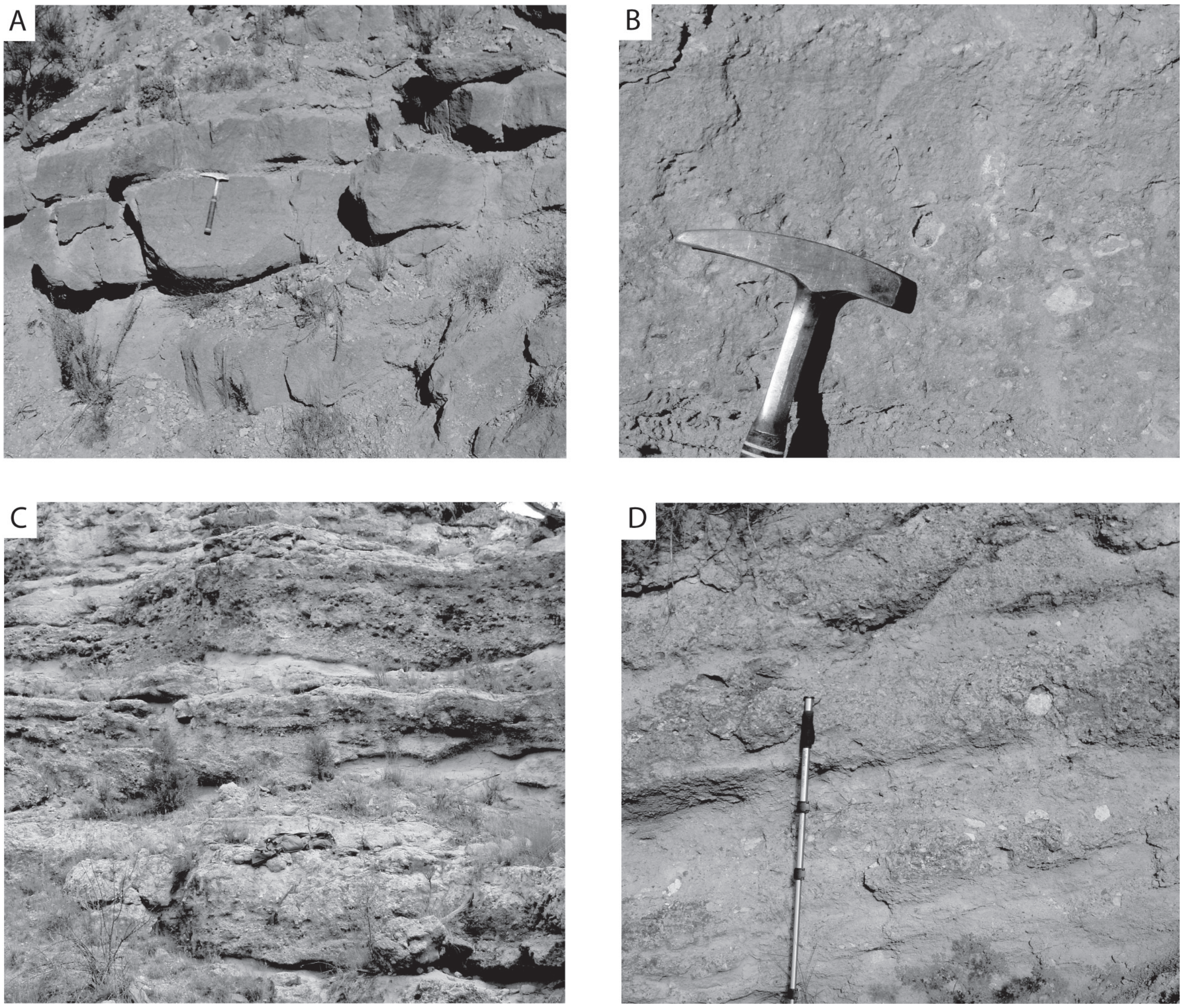

FIGURE 7. Photographs illustrating the Beartrap Canyon Formation. A) Medium to thick, tabular beds of sandstone and pebbly sandstone cemented by silica and clay; B) Close-up photograph of one of the beds in A; note the clast-supported texture of this sandstone, consistent with debris flow deposition; C) Amalgamated channel-fills of sandy conglomerate and sandstone exposed in Limestone Canyon, small tree is ~1 m tall. D) Indurated, medium-thick, tabular beds of tuffaceous gravelly sandstone; these beds are matrix-supported and interpreted as debris flows. Jacob staff is 1.5 m in length. Cobble-size clasts are composed of soft, reworked tuff. UTM coordinates (NAD 27; zone 13) of A and B: 258830 m E, 3742060 m N; UTM coordinates of C: 255815 m E, 3741400 m N; UTM coordinates of D: 261145 m E; 3729835 m N.

contrasts sharply with overlying SFG strata. Although the Beartrap Canyon Formation contains more non-welded pyroclastic rocks than the unit of East Red Canyon, the primary difference between the two units is their stratigraphic position relative to the Turkey Springs Tuff: the unit of East Red Canyon underlies this tuff whereas the Beartrap Canyon Formation overlies it (Fig. 5; Ferguson et al., 2007; Osburn and Ferguson, 2007). Because of their lithologic similarity, both units are grouped together in the geologic map of Figure 4A. The strongly cemented strata, common debris flows, and more angular clasts of the Beartrap Canyon Formation serve to differentiate it from younger SFG deposits, which are more variably cemented and generally consist of clast-supported, stream-flow sediment. The Beartrap Canyon Formation post-dates the age of the Turkey Springs Tuff (24.3 Ma; McIntosh et al., 1992), and likely extends into the earliest Miocene (Ferguson et al., 2007).

MIDDLE SANTA FE GROUP UNIT

Where exposed on the footwall of the Red Paint Canyon fault zone, in West Red and Sim Yaten Canyons, the middle SFG unit unconformably overlies the Beartrap Canyon Formation but exhibits similar or slightly less stratal tilts. Additionally, it is exposed at Ojo Caliente warm springs. Only piedmont facies were recognized in these exposures, with clast imbrications indicating westward paleoflow (Appendix 3; sites D-14 and D-255).

Description

The middle SFG unit is differentiated from the upper SFG unit by its steep dips (>15° W) and variable silica cementation (as opposed to predominately calcium carbonate cementation in the upper SFG). It contrasts with the underlying Beatrap Canyon Formation by its more rounded gravel, higher stream-flow vs. debris flow sediment ratio, and lower degree of cementation. The middle SFG unit consists of pebbly sand and sandy pebble-cobble conglomerate (Figs. 8-9). Bedding in pebbly sandstone is generally laminated to very thin and cross-stratified to horizontal-planar; foresets are up to 60 cm-thick and exhibit both tangential and planar geometries (Fig. 9). Bedding in the sandy conglomerate is very thin to medium and tabular. Gravel is mostly subrounded, moderately to poorly sorted, and consists of pebbles with 1-30% cobbles, but some beds are dominated by cobble-size clasts. Clasts are poorly imbricated and composed of diverse

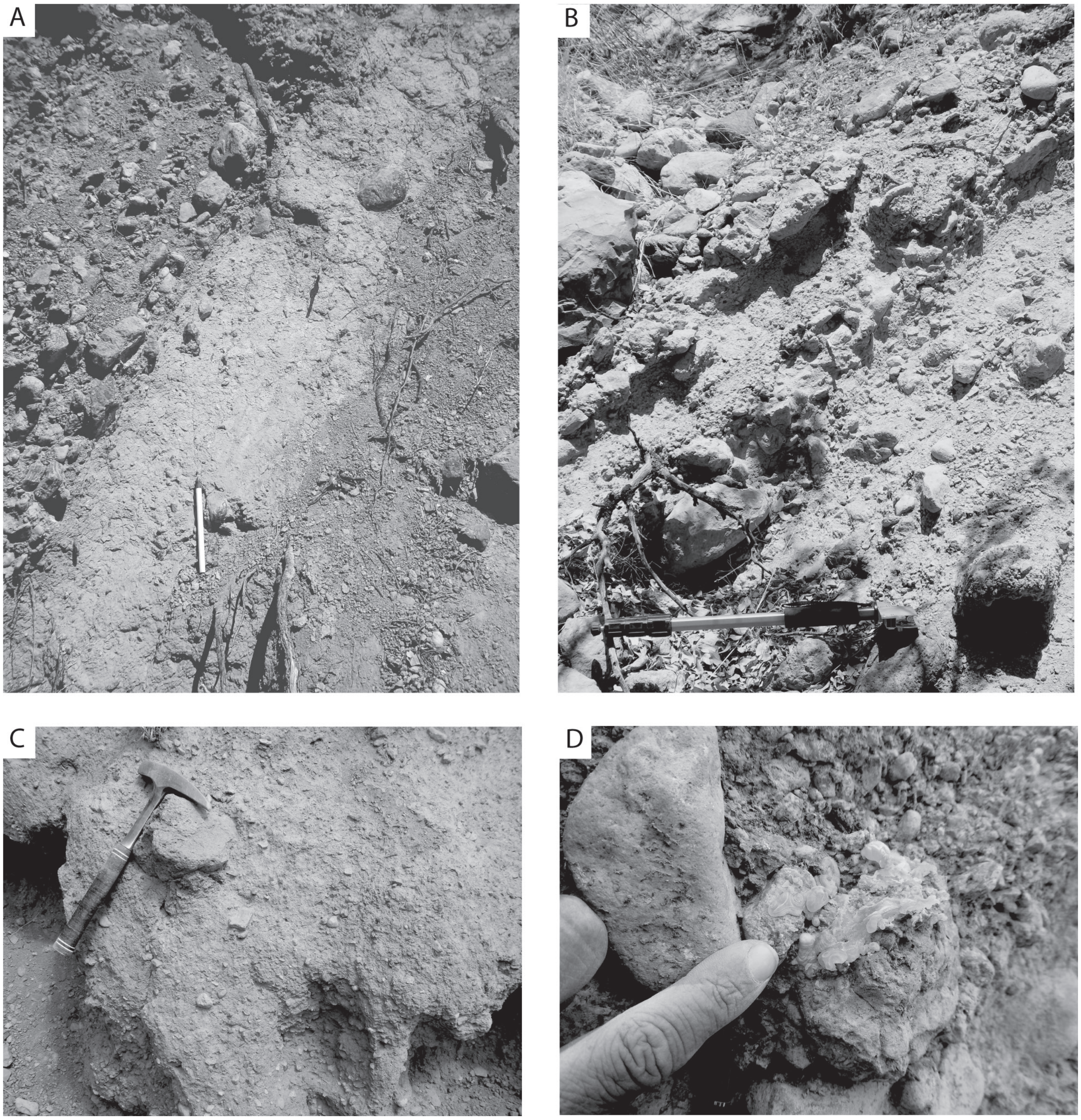

FIGURE 8. Photographs illustrating steep dips and local silica cementation of the middle Santa Fe Group unit in Sim Yaten Canyon. A and B: Steeply tilted strata, with bed attitudes averaging 350°\40°W; pen (left) and folded Jacob staff (60 cm long) for scale. C: Debris flow facies. D: Opaline(?) cementation at the outcrop shown by B.

FIGURE 9. Cross-stratified pebbly sandstone deposited by stream-flow processes; middle Santa Fe Group unit in West Red Canyon. Bedding attitude of 002°\46° W. UTM coordinates of: 261095 m E, 3729880 m N (NAD 27; zone 13).

gray-purple rhyolite, welded tuff, and minor non-welded tuff. Sand in the gravelly beds is pale brown to light yellowish brown, mostly coarse- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and a felsic-volcanic lithic arenite. Near the mountain front, there are minor thin to very thick beds of sandstone and pebbly sandstone that are internally massive; Interpret these as debris flows or hyperconcentrated flows (Fig. 8C). Strata are moderately to well consolidated and weakly to strongly cemented by silica or clay. Locally, opal precipitation is evident within the gravel (Fig. 8D). Paleosols were not observed in this unit, but exposure is limited.

Extent, Thickness, and Paleodrainage

East of the Red Paint Canyon fault zone, the middle SFG unit is inset below Beartrap Canyon Formation rhyolites and the Turkey Springs Tuff (West Red and Sim Yaten Canyons; Figs. 1,4), suggesting deposition in paleovalleys that were eroded into these older formations. Poor exposure makes thickness estimates difficult, but trigonometric calculations indicate it is at least 100 m thick in these paleovalleys. The inferred paleovalleys seen on the fault footwall may not extend west of the fault zone, especially if these faults were active during its deposition, and the contact between the Beartrap Canyon and middle SFG unit may be conformable near the center of the northern graben, similar to the contact between the lower and middle SFG in the southern Winston graben (see Cikoski and Harrison, 2012). It may be that the paleodrainage configuration was generally similar to that interpreted for the upper SFG unit (see below), with a playa existing northwest of the Monticello Box. However, it is also possible that a presumed south-flowing river in the center of the basin extended southward into the southern Winston graben.

Age

The middle SFG unit in the northern Winston graben is interpreted to be 18-23(?) Ma. It is younger than the Beartrap Canyon Formation (post-earliest Miocene). Near Ojo Caliente hot springs, two basalt flows near the apparent top of the unit returned $^{40}Ar/^{39}Ar$ ages of 18.73 ± 0.13 and 18.75 ± 0.16 Ma (McLemore, 2012; Fig. 4A). To the south, the andesite of the Winston graben overlies the middle SFG unit (Fig. 4; Cikoski and Harrison, 2012). This andesite returned an age of 18.3 ± 0.4 Ma using the K/Ar method (Seager et al., 1984). Based on these three radiometric ages, the middle SFG is interpreted to predate 18 Ma.

UPPER SANTA FE GROUP UNIT

Most of the basin fill exposed in the northern Winston graben belongs to the upper SFG unit. In this unit, I differentiated a proximal-medial piedmont, distal piedmont, and playa facies (Figs 4, 6). The proximal-medial piedmont facies was mapped where gravel and coarse sand beds dominate or are subequal to fine-grained sand and muddy sand in a given 15 m thickness, and distal piedmont facies was assigned where gravel and coarse sand beds were subordinate to fine sand and clayey-silty fine sand. In contrast to the middle SFG unit, paleosols are observed in many exposures, especially in the distal and medial piedmont facies north and northwest of the former playa. These paleosols are marked by a white calcic horizon (stage I to III carbonate morphology; see Gile et al., 1966; Birkeland, 1999) overlain by a red-orange horizon of illuviated clay. The base of the upper SFG is not exposed except on the footwall of the Red Paint Canyon and Black Range faults, where it unconformably overlies the middle SFG unit and older strata. In the center of the basin, the contact between the upper and middle SFG units is probably gradational (Fig. 5).

Description

Proximal-Medial Piedmont Facies

Gravelly beds characterize the proximal-medial piedmont facies (Fig. 10). These gravel beds are typically very thin to medium and tabular, although there are minor medium to thick, lenticular beds. Ribbon-like channel-forms are uncommon. Gravel is clast-supported, subrounded to subangular, moderately to poorly sorted, and composed of rhyolitic rocks. On the east side of the basin, these rhyolites include gray and maroon, relatively fine-grained lavas as well as welded tuffs and minor white, non-welded tuff. On the west side of the basin, rhyolite clasts also dominate, but there are minor andesitic clasts to the southwest and sparse, conspicuous green andesite(?) clasts near Wahoo Canyon. White, non-welded tuffs are observed in the northwest but are still subordinate relative to rhyolite lava clasts. In the northern basin, dacite(?) clasts are seen in some exposures but typically are less than 5%. The matrix of the gravelly sediment is commonly reddish yellow to light brown to strong brown sand with 1-10% sand-size chips composed of clay. Sand is mostly medium- to very coarse-

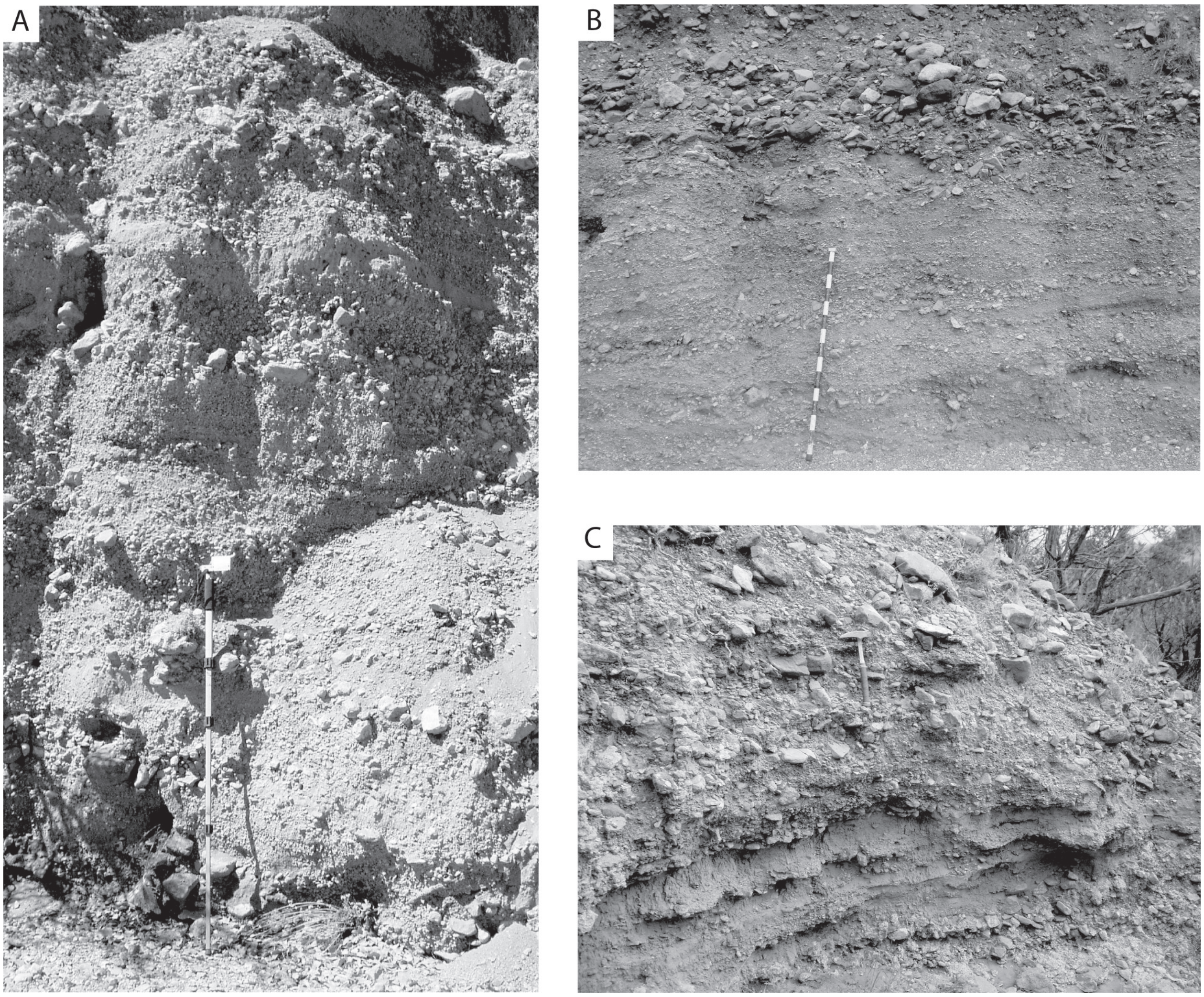

FIGURE 10. Photographs of proximal-medial piedmont facies of the upper Santa Fe Group. A) Eastern piedmont facies in West Red Canyon, 1.5 m-tall Jacob staff for scale (UTM coord: 257550 m E, 3726465 m N); B) western piedmont facies exhibiting very thin to medium, planar-horizontal bedding typical of alluvial fans, 1.5 m-tall Jacob staff for scale (UTM coord: 249415 M E, 3716875 m N); C) western piedmont facies showing minor, finer-grained extra-channel sediment near the base of the exposure, hammer for scale (UTM coord: 251315 m E, 3722590 m N). All UTM coordinates are in zone 13 and NAD 27.

grained, subrounded to subangular, moderately to poorly sorted, and a lithic arenite dominated by felsic volcanic grains. Gravelly sediment is moderately to well consolidated and generally non- to weakly cemented by calcium carbonate.

The proximal-medial piedmont facies also contains fine sand and clayey-silty fine sand beds that are subordinate or subequal to the gravelly beds. I will refer to these beds as extra-channel sediment because they appear to have been deposited outside of channels, although locally they may occupy broad channels that cannot be recognized due to limited outcrop extents. In the proximal-medial piedmont facies, this sediment is in medium to thick, tabular beds. The extra-channel sediment is reddish yellow to very pale brown to pink to light brown. Clay and silt content is estimated to range from 3 to 25%. Sand is typically very fine- to fine-grained, but locally ranges to medium-grained. Scattered within the fine sand are minor grains of coarse and very coarse sand, as well as 1-15% very fine to very coarse pebbles. Very thin to medium, lenticular beds of pebbly sediment are commonly observed in the extra-channel sediment. Extra-channel sediment is moderately to well consolidated and non to weakly cemented by calcium carbonate. The proportion of extra-channel sediment to gravelly channel-fills appears to increase up-section, as does the relative abundance of paleosols (Fig. 11).

Distal Piedmont Facies

Strata in the distal piedmont facies are similar to those in the proximal piedmont facies, but gravelly channel-fills are subordinate compared to fine sand and clayey-silty fine sand (Fig. 12). In some places, horizontal-planar bedding or low-angle cross-laminations can be observed in the extra-channel sediment. But typically the sediment is in thick beds or is massive, probably due to bioturbation. Interbedded within the extra-channel sediment is very thin to medium, lenticular beds of pebbly sediment

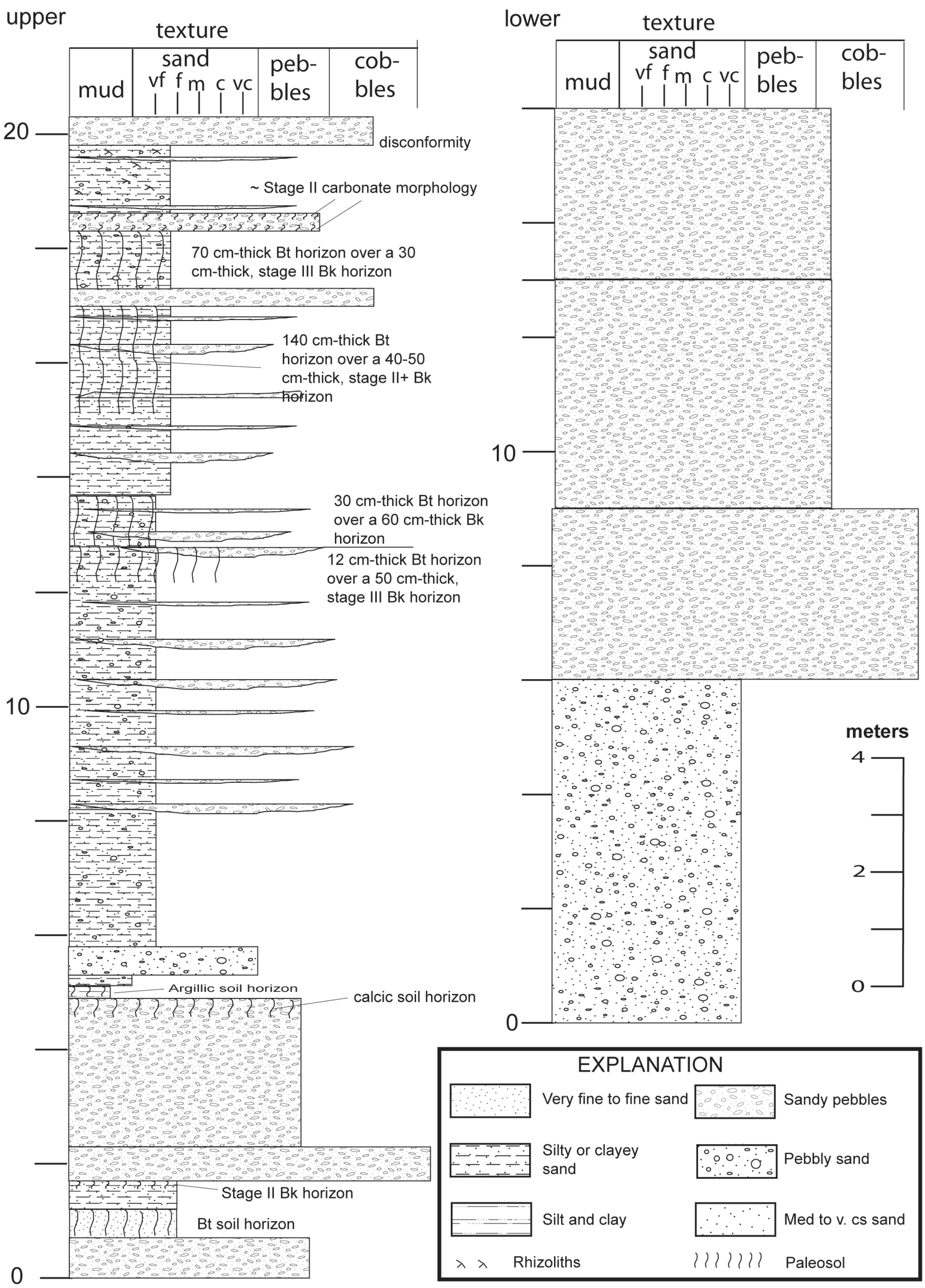

FIGURE 11. Limestone Canyon composite stratigraphic section, illustrating the medial eastern piedmont facies (including both the lower and upper sections in Appendices 1 and 2; LLCS and ULCS in Fig. 4). Note how the sediment becomes less gravelly up-section and the upward increase in the proportion of paleosols. It is uncertain whether this upward fining-trend is ubiquitous on the eastern piedmont; in contrast, the western piedmont appears to coarsen-upward. The base of the upper section and top of the lower section are separated by 25 m of elevation. See Figure 4 for locations of these stratigraphic sections, and Appendices 1 and 2 for detailed descriptions

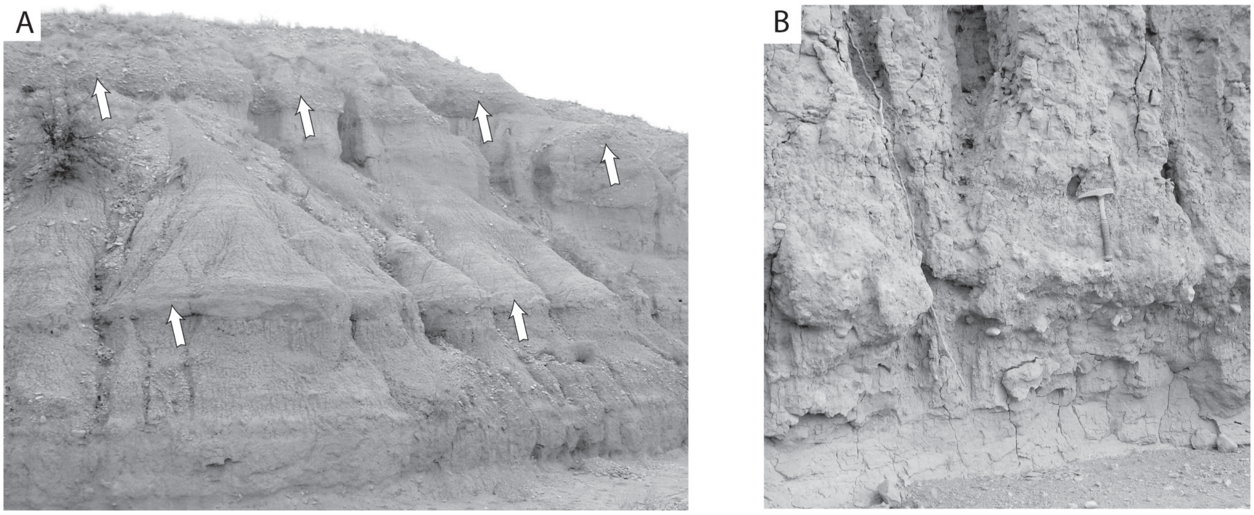

FIGURE 12. Photographs of distal piedmont sediment. A) In this 10 m-tall exposure, note that gravelly channel-fills (shown by arrows) are subordinate to finer-grained sediment. The latter is in thin to thick, tabular beds and composed of siltstone and very fine-grained sandstone. Exposure located at UTM coordinates: 253130 m E; 3725835 m N (zone 13; NAD27). B) Fine-grained, extra-channel sediment with one pebbly-cobbly bed immediately below the hammer. The extra-channel sediment is pink to light brown, hard, massive, and composed of silty-clayey very fine- to fine-grained sand, with 1-7% scattered grains of medium to very coarse sand. The gravel bed is matrix-supported and likely affected by bioturbation. Exposure located at UTM coordinates: 253890 m E; 3728220 m N (zone 13; NAD27).

and medium to thick, tabular to lenticular beds of sandy pebbles and cobbles. The gravelly beds are internally laminated to thinly bedded. If present, cementation is weak and dominated by calcium carbonate, although locally cementation is moderate to strong.

Playa Facies

At least 30 m of brown to reddish brown clay is observed near the mouths of Duck and Wahoo Canyons, about 6-8 km northwest of the Monticello Box (Fig. 13). Interbedded in this clay are minor very fine- to fine-grained sand and clayey sand beds. The clay is generally massive and the sandstone is in very thin to thick, tabular beds.

Spatial Extent and Thickness

The proximal-medial piedmont facies occupies a 2-7 km band inboard of the basin-margin faults, forming an ellipse around the basin (Fig. 4A). This band is narrowest in the west-central part of the study area, near Wahoo Canyon, and widest in the north-northeast part of the study area. The proximal-medial facies grades laterally into the distal piedmont facies in the center of the basin. Mapping of the basal contact of this unit in the vicinity of Limestone Canyon (to the northeast) and Silver Creek (to the southwest) indicates that the upper SFG unit fills irregular paleotopography (probably paleovalleys) on the footwalls of the eastern and western basin-margin faults. Previous mapping also indicates paleovalleys on fault footwalls in SimYaten and Whitewater Canyons (Ferguson et al., 2007). In the paleovalleys, the upper SFG is generally up to 60 m thick. Outside of paleovalleys, this unit onlaps Oligocene volcanic bedrock or thinly overlies (5-10 m thick, locally as thick as 35 m) broad pediment surfaces that extend up to 6 km into the highlands. Inboard of the basin margin faults, this unit is at least 100 m-thick and the base is not seen (Fig. 4).

FIGURE 13. Photograph of fine-grained sediment interpreted as playa facies. Sediment is composed of a massive clay-silt (UTM coordinates: 253230 m E; 3721130 m N; zone 13, NAD27). Hammer for scale.

The playa facies is at least 30 m thick but only near the mouths of Duck and Wahoo Canyons between 6400 and 6500 foot elevations. Very fine- to fine-grained sand becomes the dominant texture north, east, and south of lower Duck and Wahoo Canyons, and gravelly interbeds become increasingly common. Thick clay is not observed at the mouth of West Red Canyon or on the east side of Alamosa Creek north of West Red Canyon. Playa(?) clay is seen in a gully 1 km southeast of the mouth of West Red Canyon. The southern extent of the playa is uncertain because of land access restrictions. Binocular-based surveying from State Road 52 suggests the thick clay does not extend south of Knisley Canyon.

Lower and Upper Contacts

As noted above, the base of the upper SFG unit corresponds with an unconformity on the footwall of the basin-margin fault. Inboard of this faults, the base of this unit is not observed. Although there is an angular unconformity between the upper and middle SFG units in the southern Winston graben (Cikoski and Harrison, 2012), the contact is likely gradational in the center of the northern Winston graben (Fig. 4B). Due to the westward tilt of the graben, the base of the upper SFG unit is increasingly likely to be an angular unconformity as one progresses eastward from Alamosa Creek. The top of the upper SFG corresponds with a widespread erosional surface (Fig. 5), informally called the Winston surface by Harrison (1992).

Depositional Environment and Paleodrainages

In gravelly sediment of the proximal-medial piedmont facies, the ubiquitous presence of very thin to medium, tabular beds, and the paucity of ribbon-like channel-forms, is more consistent with alluvial fan deposition than the alluvial slope depositional environments described by Smith (2000) and Kuhle and Smith (2001). The paucity of matrix-supported, internally massive, gravelly beds, together with abundant clast imbrication, indicates a predominance of stream-flow deposition. A progressive increase in internally massive (bioturbated), extra-channel sediment inboard of the proximal piedmont facies suggests an increase in sheetflooding depositional processes near the center of the basin. A dominance of sheetflooding processes would be expected in the distal piedmont region, coinciding with the general downstream termination of piedmont paleo-channels. Tongues of sheetflood deposits, composed of fine-grained sand, interfinger with muddy playa facies, as noted above.

In the playa facies, the lack of reduced colors and the paucity of preserved laminated bedding argue against a long-standing body of water. This unit grades laterally into distal piedmont sediment. Thick, laterally extensive, and coarse-grained fluvial channel-fills are lacking. These observations indicate that the thick, clay-rich sediment was deposited in a playa in an arid-semiarid environment. Ephemeral stream flow from the surrounding alluvial fans deposited clay on very low or horizontal slopes in this area. Upon drying, shrinking/swelling of the clay evidently destroyed previous laminations.

Relatively abundant gravel beds in the north-central study area (i.e., in lower Big Pigeon and Limestone Canyons), corresponding with southwest flow indicators (Fig. 4A), indicates a sizeable southwest-flowing stream. Volcanic clasts in this stream are similar to the rhyolitic gravel assemblage seen in streams draining the northern San Mateo Mountains. Based on the paleoflow data and gravel composition, I interpret this stream was sourced in the northern San Mateo Mountains and approximately coincided with the location of the modern Limestone Canyon. There is no evidence of a river coming into this basin from the Plains of San Agustin (Fig. 1).

Age

The upper SFG unit in the northern Winston graben is contiguous with the upper SFG of Cikoski and Harrison (2012) in the southern Winston graben. There, the erosional surface on the upper SFG (the Winston surface of Harrison, 1992) is capped by the basalt of Tabletop Mountain (Harrison, 1994), which returned a K/Ar age of 4.8 ± 0.1 Ma (Seager et al., 1984) and an $^{40}Ar/^{39}Ar$ age of 4.91 ± 0.03 (McLemore, 2012, lower basalt). Considering the time required to form pediment surfaces (probably ~0.3-3.0 Ma; Quang et al., 2005; Tosdal et al., 1984) the age of the upper SFG unit is interpreted to be primarily middle(?) to late Miocene, consistent with Cikoski and Harrison (2012). However, it is possible that the topmost strata of the upper SFG are earliest Pliocene.

DISCUSSION

Timing of Rift Tectonism

Consistent with Cikoski and Harrison (2012) and Cather et al. (1994), I interpret that the highest extensional rates occurred in the middle and early late Miocene. This interpretation is based on comparison of dip magnitudes between the stratigraphic units, and uses an 18 Ma minimum age for the middle SFG (Fig. 14). The relative similarity of dips between the middle SFG unit and underlying volcaniclastic strata of the Beartrap Canyon Formation indicates little tilting occurred in the early Miocene. However, the ~20-30 degree discrepancy in dips between the middle and upper SFG units indicates that the bulk of tilting occurred in the middle Miocene and early late Miocene (Fig. 14).

Rift-related tilting continued into the latest Miocene and Pliocene, but probably at reduced rates. Near the Red Paint Canyon fault, upper SFG unit strata are tilted 4-11°W in Whitewater Canyon and 7-15° W in Big Pigeon Canyon. Strata only dip ~2° WNW to subhorizontal near the Black Range fault, probably because exposed upper SFG strata are younger there.

Fault scarps associated with the Black Range and Red Paint Canyon faults provide further evidence of Pliocene rift tectonism (Fig. 3). Both of these faults have offset the erosional surface developed on top of the upper SFG (i.e., the Winston surface of Harrison, 1992) by up to 15 m. These scarps have witnessed significant parallel slope retreat, degradation, and dissection, and locally have been entirely eradicated by early Pleistocene(?) ero-

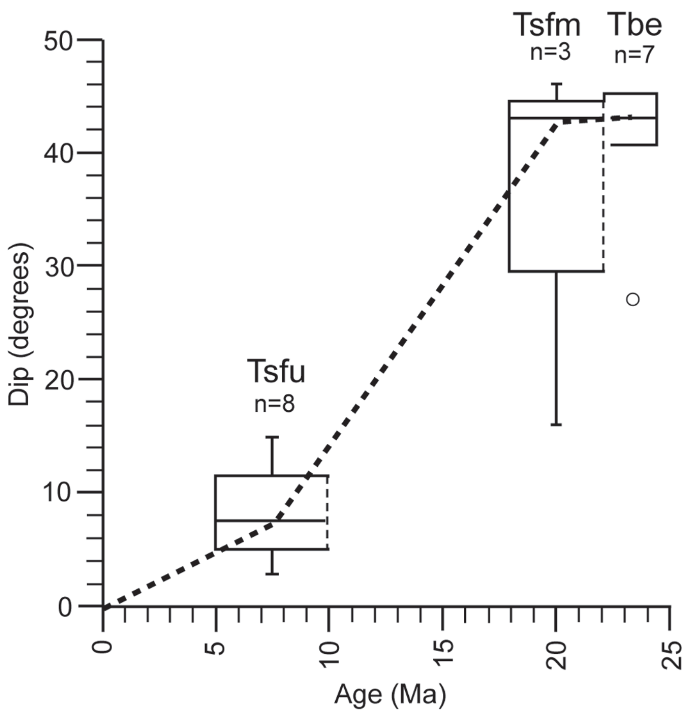

FIGURE 14. Box and whiskers plot comparing dip value statistics versus age for units Tsfu, Tsfm, and Tbe (Figure 4; upper Santa Fe Group, middle Santa Fe Group, and the combined unit of East Red Canyon - Beartrap Canyon Formation, respectively). Plotted Tbe values are located within 300 m of dip measurements of unit Tsfm. Widths of the boxes depict interpreted age range of the units, with dashed lines indicating poor age control. The top and bottom of the boxes correspond with the 25th and 75th percentiles; outliers are shown by circles. The heavy dashed line connects the median values of the units. Note the similarity of dips between units Tbe and Tsfm, and that the largest discrepancy occurs between units Tsfm and Tsfu.

sion. Consequently, I interpret minimal Pleistocene movement along these basin-margin faults.

Relation of Tectonic Activity to Upper SFG Deposition and Erosional Surfaces

Assuming basin subsidence would decrease in conjunction with a decrease in tilt rates, the latest Miocene-Pliocene would coincide with relatively low basin subsidence rates. Paleosols in the distal and medial piedmont facies of the upper SFG, which seem to be most abundant in the upper 30 m of the unit, are consistent with a progressive slowing of aggradation rates during this time of diminished tectonic activity. Waning subsidence would facilitate complete filling of the basin, eventually allowing spill-over to occur and the transition from a closed to open basin. As throw rates decreased along the Black Range fault and the basin-floor narrowed during development of a through-going river, one would expect the piedmont facies to prograde over the playa facies (e.g., Leeder and Gawthorpe, 1987; Blair and Bilodeau, 1988; Mack and Seager, 1990; McHargue et al., 1992). Although piedmont facies prograded over playa facies near the mouth of Wahoo Creek, along the western margin of the playa (Fig. 6), generally poor exposure elsewhere introduces considerable uncertainty about a basin-wide progradation.

The nature of the base and top of the upper SFG on the footwalls of basin-margin faults is noteworthy in regards to pediment formation. The paleovalleys on the footwalls were probably eroded during high subsidence rates in the middle Miocene and early late Miocene. As throw rates on the basin margin faults slowed later in the late Miocene, these paleovalleys were backfilled by the upper SFG unit. Mapping of the upper SFG basal contact on the footwalls indicates relatively planar pediment surfaces between the paleovalleys, which are overlain by relatively thin upper SFG sediment (Figs. 4, 15). I interpret these pediment surfaces formed in the latest Miocene to earliest Pliocene, after the paleovalleys aggraded but prior to the emplacement of the 4.9 Ma lower basalt of Tabletop Mountain. This coincides with a time of decreasing tectonic activity and aggradation rates, as reflected in the relatively low dips of the upper SFG unit and abundant paleosols, and precedes middle Pleistocene valley incision. The presence of calcic horizons indicates that the paleoclimate was probably semiarid. Pediments are overlain by the upper SFG, which is generally 5-10 m thick but locally as thick as 35 m. Thus, this pediment appears to have formed in a semiarid climate during a time of slowly rising or stable base levels and low fault throw rates.

Initiation of the extensive, relatively flat erosional surface on top of the upper SFG (i.e., the Winston surface of Harrison, 1992) occurred in the earliest Pliocene because the 4.9 Ma basalt of Tabletop Mountain overlies it. Widespread surface denudation probably continued well into the Pliocene and early Pleistocene, coinciding with a time of aggradation in the Engle Basin to the southeast (Fig. 5). If so, erosion in the Winston graben supplied sediment to the aggrading Palomas Formation in the Engle basin. The discrepancy between Pliocene erosion in the Winston graben

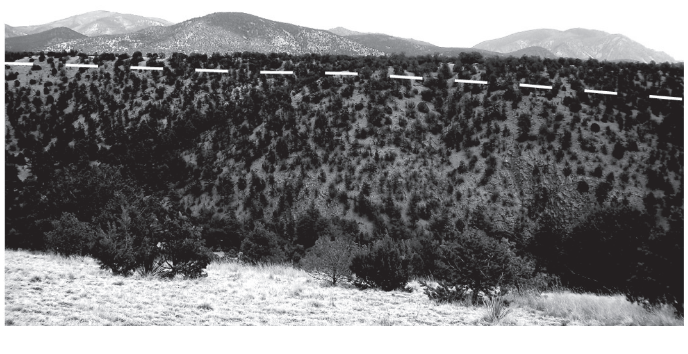

FIGURE 15. Photograph of pediment and overlying upper SFG unit (5-10 m-thick) on the south side of Sim Yaten Canyon. Pediment surface shown by dashed white line. Southern San Mateo Mountains are in the background.

and aggradation in the Engle basin is attrbuted to continued normal faulting and tectonic subsidence in the Engle basin after waning of tectonic subsidence in the Winston graben (Fig. 5).

CONCLUSION

The SFG in the northern Winston graben overlies the Beartrap Canyon Formation and Turkey Springs Tuff, in addition to older Oligocene volcanic and volcaniclastic rocks. Although bounded by faults on both sides, SFG bedding attitudes and gravity data indicate that this structural depression is an asymmetric, west-tilted graben. The middle SFG unit is exposed on the footwall of the eastern boundary fault, the Red Paint Canyon fault zone, and is 18-23(?) Ma in age based on radiometric dating of volcanic flows. Approximately similar bed attitudes between this unit and underlying Beartrap Canyon Formation strata indicate low tilting rates of the graben prior to ca. 18 Ma. The upper SFG unit underlies most of the modern surface of the basin. It is generally weakly to non-cemented and exhibits low stratal dip magnitudes (0-15° W). Overlain by a 4.9 Ma basalt to the south, the upper SFG unit is primarily middle(?) to late Miocene in age, with topmost strata possibly being earliest Pliocene. The 20-30 degree dip discrepancy between the middle and upper SFG indicates significant tectonic tilting occurred between 18 Ma and the latest Miocene. Rates of tectonic tilting, and presumably basin subsidence, are interpreted to have lessened in the latest Miocene and Pliocene. SFG aggradation rates also slowed down during this period, consistent with the presence of distal-medial piedmont paleosols in the upper part of the upper SFG unit. Reduced throw rates on the basin-margin faults allowed the SFG to back-fill footwall paleovalleys in the latest(?) Miocene. Pediments between the paleovalleys are interpreted to have formed in the latest Miocene-earliest Pliocene, during a time of slowly rising or stable base levels, lower fault throw rates, and an inferred semiarid climate. These pediments were buried by 5-10 m of uppermost SFG strata, locally as thick as 35 m. Denudation resulting in broad, relatively planar erosion surfaces characterized the Pliocene-early Pleistocene; the resulting detritus was carried by Alamosa Creek into the Engle Basin to the southwest. In this part of the Rio Grande rift, an inward concentration of extensional strain in the Pliocene apparently resulted in relatively stable base levels in outer basins of the rift, such as the Winston graben, and allowed >100-130 m of sedimentation in the subsiding center of the rift.

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Basal portion of a cross-stratified eolian sandstone set in the unit of East Red Canyon (late Oligocene) in the San Mateo Mountains in Socorro County New Mexico, May 1984. NMBGMR Photo Archive No. p-01236