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Colin T. Cikoski and Richard W. Harrison

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STRATIGRAPHIC AND STRUCTURAL DEVELOPMENT OF THE SOUTHERN WINSTON GRABEN, RIO GRANDE RIFT, SOUTHWESTERN NEW MEXICO

COLIN T. CIKOSKI[1] AND RICHARD W. HARRISON[2]
[1]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Pl, Socorro, NM 87801
[2]U.S. Geological Survey, 12201 Sunrise Valley Dr, Reston, VA, *colintc@nmbg.nmt.edu

Abstract—Recent field work near the southern terminus of the north-trending, late Oligocene to early Pliocene Winston graben (WG) provides details into the interrelated stratigraphic and structural development of the graben. A 5-10° angular unconformity between the 28.9 Ma Vicks Peak Tuff (Tvp) and the 29.4 Ma tuff of Little Mineral Creek (Tlmc) suggests extensional fault block tilting and graben development began circa 29 Ma. Overlying Tvp and Tlmc are interbedded conglomerates and tuffs, including one tentatively correlated to the 27.7 Ma South Canyon Tuff that are assigned to the lower Santa Fe Group (SFG). The irregular, erosive basal contact of the lower SFG suggests initial graben subsidence was minimal. Conformably overlying the tuff-bearing conglomerates is the widespread middle SFG unit consisting of a sandstone to mudstone fine-grained facies and a conglomeratic coarse facies. The distribution of facies and the directions of clast imbrications in this unit suggest derivation from both eastern and western highlands, and also suggest the presence of a southward-flowing, fine-grained axial drainage that terminated at a lake or playa. The middle SFG is capped by the 18 Ma andesite of the Winston graben (Twa) on the east side of the basin, and by an angular unconformity on the west, with the dividing line between these two domains being the Cuchillo Negro uplift (CNU), a moderately east-tilted intrabasinal horst. This horst may have acted as a topographic barrier to limit the extent of Twa. Above Twa and the angular unconformity, the upper SFG also shows evidence for derivation from both eastern and western highlands, and is truncated by a pediment that is locally capped by the 5 Ma basalt of Tabletop Mountain (Ttb). Bound by large faults on both the east and west, the WG generally resembles a symmetric graben. In the southern WG, however, SFG deposits dip westward on the west side of the basin and eastward on the east side, suggesting the graben developed at least in part as a pair of narrow asymmetric half-graben of opposing polarity. The divide between the two dip domains lay along the west side of the CNU. Offset along the eastern graben-bounding fault is apparent in deposits as young as Ttb, suggesting graben subsidence continued into at least the early Pliocene. No deformation is apparent in inset Pleistocene terrace deposits.

INTRODUCTION

In south-central New Mexico, the Rio Grande rift consists of a series of dominantly north-south elongate extensional basins and highlands typically bound by normal faults. The progressive development of these basins is recorded in the characteristics and deformation of the volcanic and sedimentary strata that fill the basins. The Winston graben is one such basin lying along the western flank of the rift. Flanked by the Black Range on the west and the Sierra Cuchillo on the east, the graben is narrow and elongate north-northwest to north-northeast (Fig. 1). Harrison (1990, 1994) established the volcanic and basic Santa Fe Group (SFG) stratigraphy of the graben, as well as the Eocene to recent structural history, in his detailed work on the Black Range. More recent work by Cikoski (unpubl.) on the Winston 7.5-minute quadrangle in the Fall of 2011 expanded upon Harrison's work, concentrating on the sediments and deformation of the SFG. This report focuses on the preliminary results and interpretations of this more recent mapping. Additional data was gleaned from reinterpretation of the work of Jahns et al. (2006) on the Chise quadrangle to the east of the Winston quadrangle.

This current work focuses on the southern Winston graben, which here refers to the area south of the town of Winston, to the southern terminus of the graben at the east-northeast-trending structural high along the Chise lineament of Harrison (1990; Figs. 1, 2). This area is of particular interest because it is the only area with continuous exposure of the rocks associated with the early development of the graben, and hence presents the best record of its early development.

STRATIGRAPHY

Pre-Santa Fe Group units

In this report, pre-SFG units are divided into the Datil Group, undivided, the basaltic andesite of Poverty Creek, the tuff of Little Mineral Creek, and the Vicks Peak Tuff (Table 1). Each of these units is described in more detail by Harrison (1990, 1994) and references therein, and the interested reader is referred to those publications for more information.

Following the definition of Cather et al. (1994a), the Datil Group contains all late Eocene-early Oligocene volcanic strata up to the 31.8 to 29.4 Ma regional hiatus in volcanism ($^{40}Ar/^{39}Ar$ ages for interval modified from McIntosh et al., 1991; see footnotes for Table 1). In the study area, this includes: the tuff of Rocque Ramos Canyon, a moderately to poorly welded, moderately crystal-rich ash flow tuff with an $^{40}Ar/^{39}Ar$ age of 35.4 Ma; the Kneeling Nun Tuff, a regionally extensive, poorly to moderately welded, crystal-rich ash-flow tuff with an $^{40}Ar/^{39}Ar$ age of 35.3 Ma; and the Cuchillo Negro complex of Harrison (1990), a local intrusive-extrusive complex, consisting of intrusive basaltic andesite and trachyandesite, intrusive and extrustive rhyolite, three local ash-flow tuffs, and associated volcaniclastic sediments (Table 1; ages modified from McIntosh et al, 1991; descriptions from Harrison, 1990).

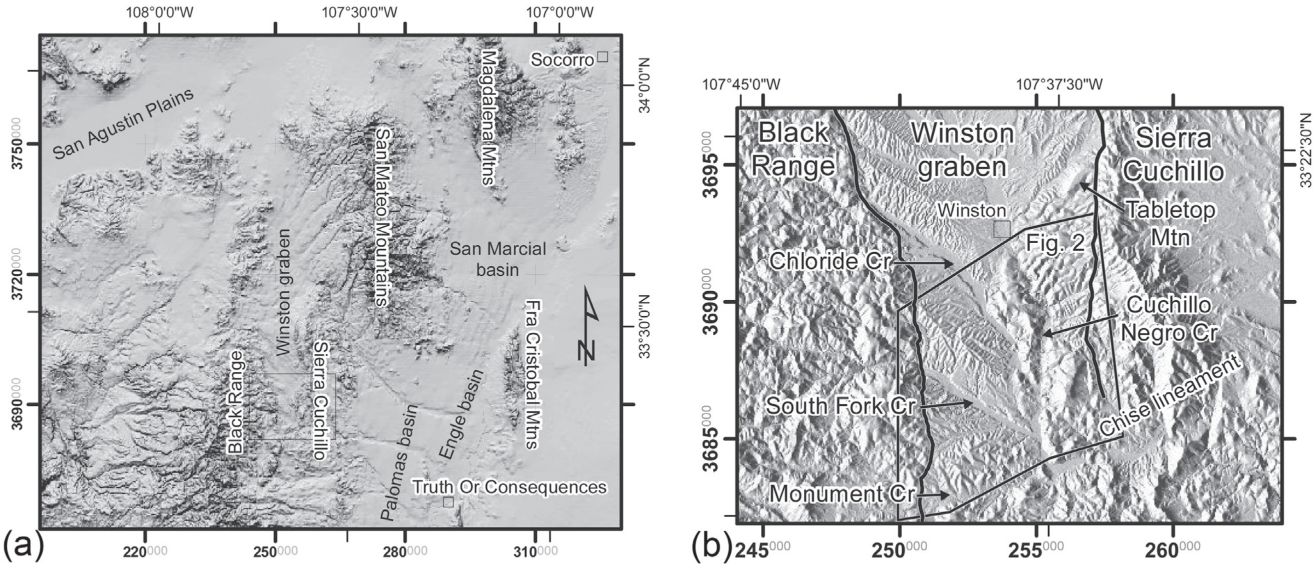

FIGURE 1 – Basins and ranges of the southern Rio Grande rift, showing the locations of the Winston graben (a) and the study area (b). Both images are hillshade DEMs with NAD27 UTM Zone 13S grids. (a) Location of the Winston graben. Small boxes are cities, and the larger rectangle locates (b). Some uplifts and basins of the Rio Grande rift are labeled. (b) Detail location figure, with geographic terms used in the text. Thin black line outlines the study area (Figure 2). Thick black lines locate the graben-bounding faults. The southern boundary of the graben is the Chise lineament, along which pre-rift strata rise to the surface along a complex of faults (not shown). Small box locates the town of Winston. "Cr" - Creek.

Elston et al. (1973) and Coney (1976) used the term basaltic andesite of Poverty Creek to refer to a sequence of dark, mostly aphanitic lavas in the northern Black Range. C.E. Chapin (pers. comm., cited in Harrison, 1990, 1994) determined a K-Ar age of 29 Ma for this unit for a sample from a vent that now lay within the graben (Table 1). The character, age, and chemistry of the unit indicates it is a part of the widespread SCORBA suite of Cameron et al. (1989), which is generally thought to be associated with early extensional stress regimes in the southwestern USA and northwestern Mexico (Cameron et al., 1989; Harrison, 1990; and references therein). The basaltic andesite is correlative to the "lower andesite sequence" of Jahns et al. (2006).

The tuff of Little Mineral Creek is a local, poorly welded, lithic-rich to very lithic-rich, crystal-poor ash-flow tuff, with an $^{40}Ar/^{39}Ar$ age of 29.4 Ma (Table 1; McIntosh et al., 1991). The tuff is thought to have erupted from the area of Cobb Mountain, 6 to 7 km west-southwest of Figure 2 (Harrison, 1990, 1994). It is generally correlative to the "tuff breccia" (Trb) unit of Jahns et al. (2006).

The Vicks Peak Tuff is a regionally extensive ignimbrite with an $^{40}Ar/^{39}Ar$ age of 28.9 Ma that erupted from the Nogal Canyon cauldron (or caldera) in the southern San Mateo Mountains, ~20 km northeast of the study area (Table 1; McIntosh et al., 1991; Chapin et al., 2004). It is a moderately to densely welded, crystal-poor ash-flow tuff with conspicuous large, elongate pumice bearing a granular texture from vapor-phase mineralization (Harrison, 1990, 1994). It rests upon the tuff of Little Mineral Creek or the basaltic andesite of Poverty Creek with slight (5-10°) angular unconformity (Fig. 3; see also Harrison, 1990, 1994), suggesting that initial fault block tilting and graben development began between the eruptions of the two tuffs. Despite its regional extent, the Vicks Peak Tuff is notably absent from the northern Black Range, and is only locally present within the Winston graben itself. The tuff crops out in the south portion of the study area in a narrow band found only in the hills between South Fork and Monument Creeks (Figs. 2, 3). The overlying lower SFG unit appears to thicken where the tuff is absent, suggesting the cause of pinchout is local erosional stripping of the tuff by the streams carrying the lower SFG sediment. The erosional nature of this contact would suggest that although graben development began prior to the eruption of the Vicks Peak Tuff, not enough accommodation space was generated during this period to completely bury and preserve the tuff. The tuff also crops out in the northeast corner of Figure 2 as what appears to be a gravity-slide block, described in more detail by Harrison (1990, 1994).

Santa Fe Group and intercalated volcanic rocks

The Santa Fe Group (SFG) consists of all sedimentary basin fill associated with extensional basins of the Rio Grande rift up to and including the highest aggradational surface of the basin fill (Hawley et al., 1969). An ambiguity to this definition is that it can be difficult to conclude whether or not a given sedimentary unit accumulated in an extensional basin associated with rifting. Given that graben development appears to have begun in the Winston area prior to the eruption of the Vicks Peak Tuff, we suggest that all sedimentary deposits in the area overlying the tuff accumulated in a rift-related basin or basins, and hence belong to the SFG. The SFG in the southern Winston graben is divisible into lower, middle, and upper units, based on the presence of

TABLE 1: Pre-Quaternary stratigraphy of study area (Fig. 1). Units are generally listed in chronologic order, oldest at the bottom, except for the two middle SFG units, which are coeval, and the boulder-rich SFG unit, which is coeval with the middle and upper SFG. Patterns are given for those map units highlighted with a pattern or fill in Figures 2 through 4.

Unit	Map abbr	Age[1] in Ma (2σ error)	Abbreviated description
Basalt of Tabletop Mountain	N/A	4.8 (0.1)[2,*]	Light gray to black flow, with sparse phenocrysts of olivine, pyroxene, plagioclase
Boulder-rich SFG	Tsfb		Poorly exposed, very poorly sorted cobble and boulder conglomerates
Upper SFG	Tsfu		Poorly indurated, poorly sorted pebble conglomerates to rare sandstones
Andesite of the Winston graben	Twa	18.3 (0.4)[2,*]	Dark gray to dark reddish gray, aphanitic to fine-grained flows, with rare phenocrysts of plagioclase
Middle SFG - coarse facies	Tsfm		Moderately indurated, poorly sorted cobble and pebble conglomerates
Middle SFG - fine facies	Tsfms		Poorly indurated, poorly sorted sandstones, siltstones, and mudstones
Lower SFG	Tsfl	27.73 (0.14)[+]	Interbedded tuffaceous conglomerates and sandstones and lithic-rich, poorly welded tuffs
Vicks Peak Tuff	Tvp	28.93 (0.12)	Moderately to densely welded, crystal poor ash-flow tuff with conspicuous large elongate pumices
Tuff of Little Mineral Creek	Tlmc	29.39 (0.20)	Poorly welded, very lithic-rich and crystal-poor ash-flow tuff
Basaltic andesite of Poverty Creek	Tpc	28.8 (0.6)[3,*]	Dark, generally aphanitic lava flows
Datil Group	Td		
•Cuchillo Negro complex		•34.7 (0.8)[3,*]	•Highly variable intrusive-extrusive complex
•Kneeling Nun Tuff		•35.34 (0.10)	•Moderately welded, crystal-rich ash-flow tuff
•Tuff of Rocque Ramos Canyon[§]		•35.41 (0.08)	•Moderately welded, moderately crystal-rich ash-flow tuff

[1]: Ages are $^{40}Ar/^{39}Ar$ ages modified from McIntosh et al. (1991) unless noted. Ages presented here are scaled upwards by 1.3% from McIntosh et al. to account for changes to the accepted Fish Canyon Tuff sanidine monitor age. McIntosh et al. originally used a monitor age of 27.84 Ma, but Kuiper et al. (2008) suggest an age of 28.201 Ma better aligns the argon technique with astronomical ages.
[2]: Age from Seager et al. (1984).
[3]: Age from Chapin (pers. comm., cited in Harrison, 1994).
*: K-Ar age. K-Ar ages are not modified from the original publications.
[+]: Age of the South Canyon Tuff, to which a marker tuff intercalated with the lower SFG is tentatively correlated (Harrison, 1990, 1994).
[§]: The tuff of Rocque Ramos Canyon most likely correlates to the Bell Top tuff 4 (McIntosh et al., 1991) , and the presented age is the average of ages from one sample of the tuff of Rocque Ramos Canyon and two from the Bell Top tuff 4.

intercalated volcanic strata and an angular unconformity (Fig. 4). Radioisotopic age controls are provided by the intercalated volcanic rocks (Table 1), described in more detail below. In addition, Jahns (1955) reported collecting Quaternary invertebrate fauna from SFG strata about 10 km north of Figure 2. This age control, however, is in disagreement with the 5 Ma K-Ar age for the basalt of Tabletop Mountain (Table 1), which caps the SFG 1-1.5 km north of the study area (Fig. 1). As Jahns' mapping does not differentiate between SFG and inset post-SFG terrace deposits, it is possible this fauna actually belonged to a post-SFG deposit. Because of this uncertainty, we choose not to incorporate Jahns' age control in the following discussion, and instead accept the K-Ar age as a minimum age for the SFG within the study area.

Lower Santa Fe Group

The lower SFG consists of interbedded tuffaceous pebble to cobble conglomerates, moderately lithic-rich tuffs, and tuffaceous sandstones. It is well exposed along South Fork Creek, where altered outcrops are mined by the St. Cloud zeolite opera-

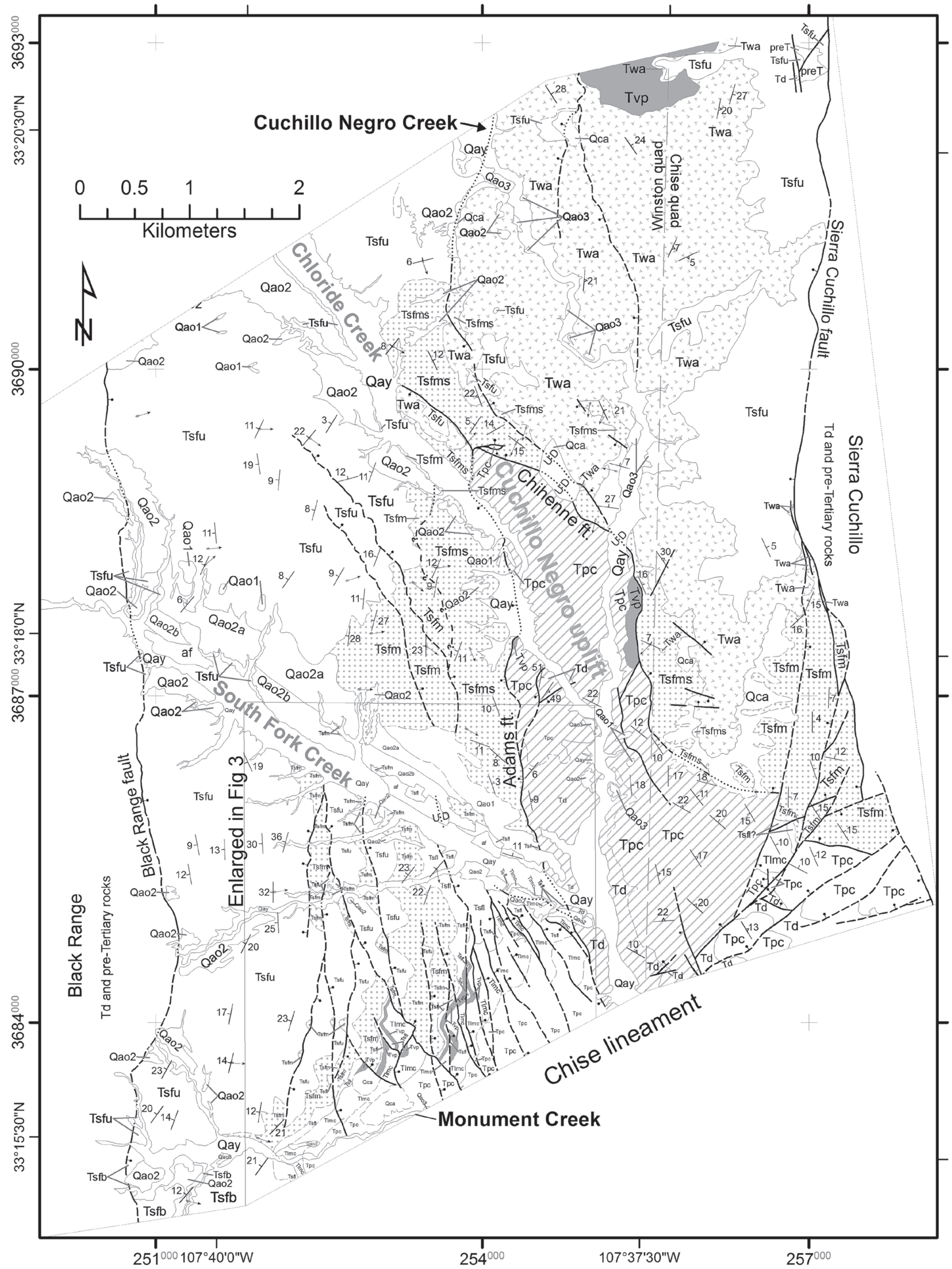

FIGURE 2 – Generalized geologic map of the study area. Hachured area highlights Oligocene volcanic rocks associated with the Cuchillo Negro uplift. Arrows are paleocurrent directions from imbrication and channel axis measurements (Tsfl) or simply imbrication measurements (all other units). Bedding and foliation attitude symbols are as normal. Dashed gray line separates the Winston and Chise quadrangles; Winston data from Harrison (1990) and Cikoski (unpubl.), Chise data adapted from Jahns et al. (2006) and Cikoski (unpubl.) UTM grid is from NAD27 Zone 13S. Pre-Quaternary unit abbreviations and map symbols are shown in Table 1. Other abbreviations: preT – pre-Tertiary rocks, undivided; Qa_ - post-SFG alluvial units separated by elevation, Qao1 as the oldest and highest, and Qay as the youngest and lowest; Qca – colluvium and minor alluvium burying important geologic features; 'ft.' - fault.

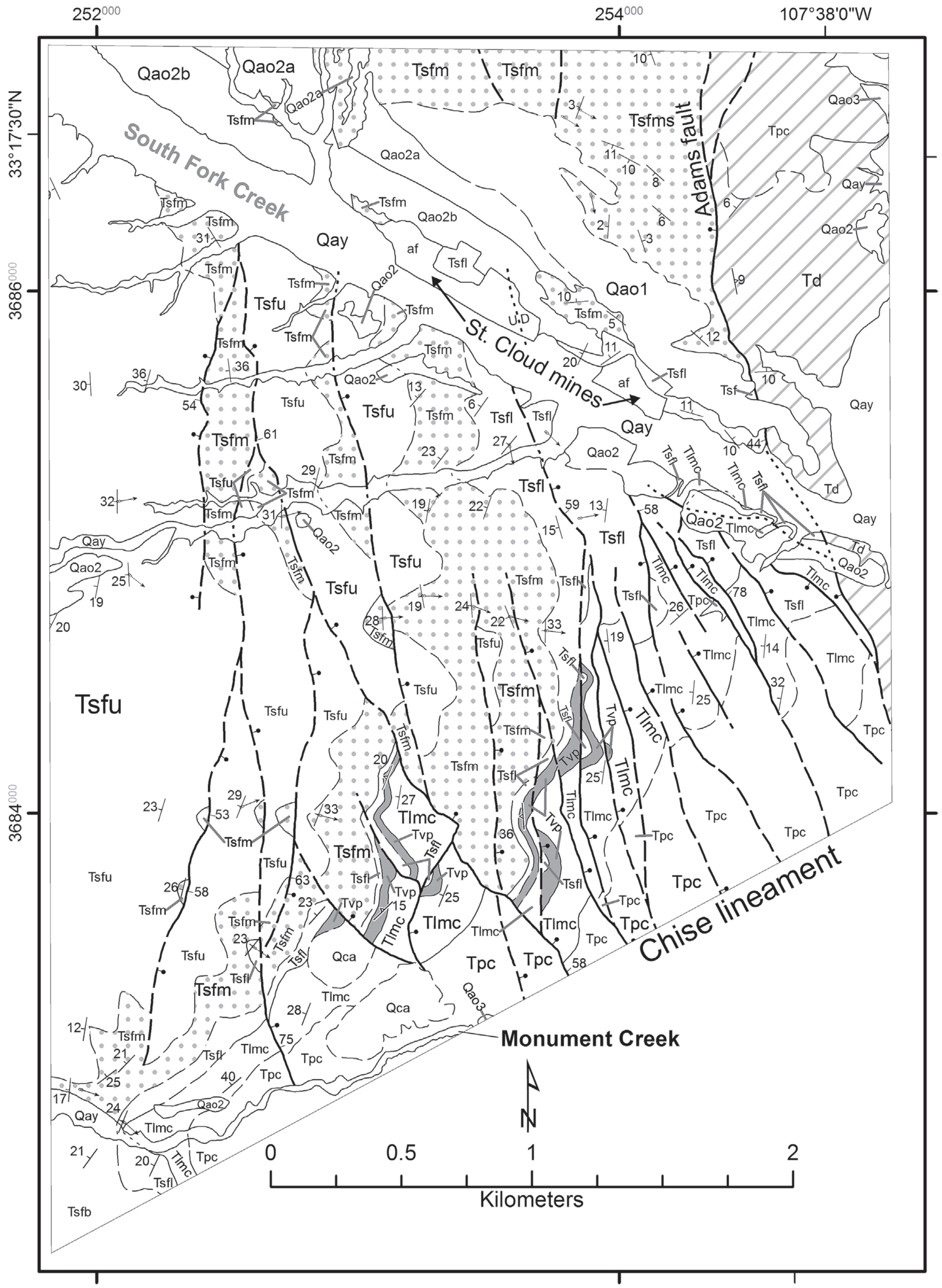

FIGURE 3 – Detail generalized geologic map for the complex southern portion of the study area. Same abbreviations and symbology as shown in Table 1 and Figure 2.

tion, and locally exposed in the hills to the south (Figs. 2, 3). Conglomerates consist of poorly sorted, subangular to rounded, fine to coarse pebbles with rare cobbles and boulders, dominantly of rhyolitic composition but with sparse andesites. Sandy matrices and sandstones consist of poorly sorted clayey fine to coarse sand. Beds are typically discontinuous and conglomerates are often channel-shaped. Cross-bedding is common to channels, as is normal grading. Paleocurrent directions were measured in only three outcrops, but channel axes (total of 12 measurements) appear to be dominantly oriented northwest-southeast, while imbrication directions (averaged from 15-17 individual measurements at each outcrop) commonly indicate east-southeast paleoflow. Taken together, we interpret a dominantly southeastward paleocurrent direction.

Tuffs are poorly to non-welded, crystal poor, and moderately lithic-rich (5-25% by volume). Thinner tuffs (1 to 1.5 m thick) are discontinuous, but one "marker" tuff, found at or near the top of the lower SFG, is up to 8 m thick and appears to be continuous across the mapped extent of the unit. Harrison (1990) tentatively correlated this marker tuff to the 27.7 Ma South Canyon Tuff (Table 1), based on its similar lithologic character to another tuff interbedded with similar sediments (the sandstone of Inman Ranch of Eggleston, 1987) found in Scales and Stiver Canyons, 14 to 20 km northwest of the study area. McIntosh et al. (1991) correlated the tuff in these Canyons to the South Canyon Tuff based on a distinctive remnant magnetism direction and an $^{40}Ar/^{39}Ar$ age of 27.6 Ma. Some smaller mapped extents of the "tuff breccia" (Trb) unit of Jahns et al. (2006) may also correlate to the South Canyon Tuff.

As discussed previously, the basal contact for the lower SFG unit is irregular and erosive. In the hills between South Fork and Monument Creeks, the lower SFG rests upon the Vicks Peak Tuff (Figs. 2, 3, 4), but along the creeks themselves the lower SFG overlies the tuff of Little Mineral Creek with angular unconformity. Where the Vicks Peak Tuff is missing, the lower SFG appears to thicken, according to map patterns (Figs. 2, 3). In addition, along some well-exposed minor streams where the Vicks Peak Tuff is best exposed, the lower SFG unit is particularly thin, being locally represented solely by the marker tuff, with no associated sedimentary strata present. These observations suggest that the lower SFG was deposited by laterally-restricted streams that incised deeply into underlying strata then back-filled, without extensive lateral meandering and planation.

Similarities in sediment characteristics and age controls suggest the lower SFG in the Winston graben may correlate to the Thurman Formation, a highly tuffaceous sandstone, with lesser mudstones, rare conglomerates, and rare ash-fall beds, exposed in the southern Caballo Mountains (Seager and Mack, 2003). Based on detrital single sanidine crystal $^{40}Ar/^{39}Ar$ ages and paleomagnetism, Boryta (1994) suggested the timing of Thurman Formation deposition spanned the eruption of the South Canyon Tuff, which, given the tentative correlation of the marker tuff to the South Canyon Tuff, would make the Winston graben lower SFG and the Thurman Formation at least in part age correlative. The two units are also lithologically comparable, insofar as they are both very ash-rich alluvial deposits. The Thurman Formation is thought to be the distal portion of a volcaniclastic apron that emanated from the Mt Withington caldera in the northern San Mateo Mountains (Mack et al., 1998; Seager and Mack, 2003), approximately 45 km north-northeast of the study area. It is possible the Winston graben lower SFG is also related to this apron.

Middle Santa Fe Group

The middle SFG consists of pebble to cobble conglomerates, sandstones, siltstones and local mudstones. It is divisible into fine (Tsfms) and coarse (Tsfm) facies (Table 1, Fig. 4). The former is found near the center of the graben around present-day Chloride and Cuchillo Negro Creeks (Fig. 2), and consists of areas with ratios of sandstones, siltstones, and mudstones to conglomerates greater than 1:1. Sandstones and siltstones consist of poorly sorted silts to medium sands in varying proportions, commonly with sparse fine pebbles but locally with abundant fine to medium pebbles. Mudstones, found only around the St. Cloud mines, are also poorly sorted, with a few percent silt and fine to medium sand grains visible in otherwise very fine grained rocks. Rare pumiceous pebbles up to 1 cm across are also found in the mudstones. All three lithologies are typically weakly cemented and tabular, with vague thin bedding or laminae, although sandstone beds with channel shapes and cross-bedding also locally occur.

The coarse facies consists of conglomerates interbedded with rare sandstones and siltstones. Conglomerates consist of very poorly to poorly sorted, angular to rounded pebbles and cobbles with rare boulders. Coarse pebbles and cobbles typically dominate beds of this unit, making it noticeably coarser than the overlying upper SFG unit. On the Winston quadrangle, clasts are dominantly rhyolites, with rare to common andesites comprising up to 20% of outcrops. Matrices are of fine to medium sand, with variable silt. Beds are tabular to channel-shaped, in roughly equal proportions, with cross-bedding in some channels, and uncommon normal grading. The contact between the fine and coarse facies appears to be interfingering.

The middle SFG unit is correlative to the undivided "rhyolite-trachyte sequence" (Tr) of Jahns et al. (2006) where it is found along the western margin of the Chise quadrangle. Although they describe the sequence as primarily tuff and tuff breccia, reconnaissance work in the area of Figure 2 found only sandstones, siltstones, and minor conglomerates. Their "conglomerate" subunit (Trc) is here interpreted as the coarse facies of the middle SFG, whereas the undivided Tr unit is considered to correlate with the sandstone- and siltstone-dominated facies.

Paleocurrent directions from clast imbrications (averages of 10-30 individual imbrication measurements at 33 outcrops) indicate eastward paleoflow on the west side of the graben and commonly southward transport in the central portion (Figs. 2, 3). Along the east edge of the Winston quadrangle, distinctly westward or southwestward imbrications were measured in four outcrops; no imbrication measurements were made further east on the Chise quadrangle. This pattern of imbrication directions indicates that sediment-transporting streams originated in both eastern and western highlands, and suggests the presence of an axial drainage that flowed southward toward the area of the St. Cloud mining operations. Facies distributions corroborate this pattern, as conglomerates dominate along the western and eastern margins of the graben, sandstones and siltstones dominate in the center, and mudstones are locally found at the southern end of the mapped extent of the fine facies (Figs. 2, 3). The mudstones may be the product of a lake or playa lying at the terminus of a closed

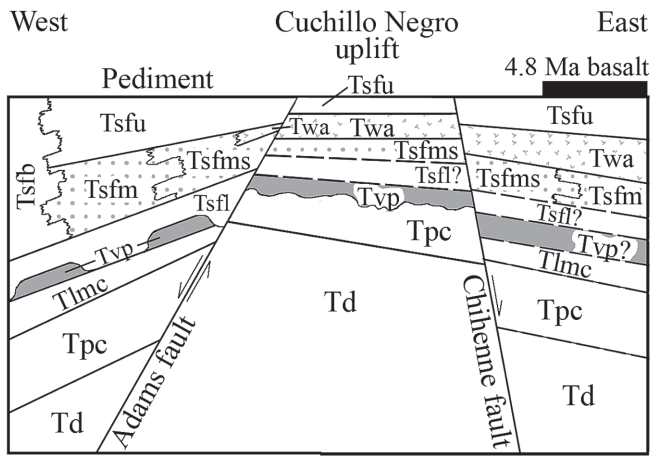

FIGURE 4 – Simplified depiction of the stratigraphy of the study area. Variability in bedding dip directions and magnitudes and in unit thicknesses relative to the Cuchillo Negro uplift are shown diagramatically. Same abbreviations and symbology as shown in Table 1 and Figure 2. Dashed contacts bound units not observed in the field by the authors; these units may not exist throughout the study area.

drainage network. The presence of such a lake was also suggested by Bowie and Barker (1986) to explain the zeolitization of the lower SFG and tuff of Little Mineral Creek in the area of the St. Cloud mines, near to where the mudstones are found.

The base of the coarse facies is a gradational contact with the underlying lower SFG, such that the prevalence of ash-rich sandy matrix and the number of ash-rich sandstones decrease up-section. The contact is placed at a marked decrease in induration and matrix content that coincides with a decrease in the abundance of cross-bedding and a slight increase in average clast size. In the poorly exposed and highly faulted area south of South Fork Creek, the location of the contact is often determined by the location of the continuous marker tuff found toward the top of the lower SFG sequence. The basal contact of the fine facies is not exposed, but is likely a gradational contact as well.

Andesite of the Winston graben

The andesite of the Winston graben was informally named by Harrison (1990) for a large flow-dome complex and related outflow lava that occurs in the southern part of the graben. The flows are dark gray to dark reddish gray and aphanitic to fine-grained, with rare, small (<1 to 3 mm across) phenocrysts dominantly of plagioclase but also locally of olivine, pyroxene, and biotite. Individual flows are typically discontinuous, although some can be followed laterally up to 600 m, and autobrecciated tops and bottoms are common. Seager et al. (1984) dated a sample of the andesite from a wash due east of the town of Winston by the K-Ar method at 18 Ma (Table 1).

Jahns et al. (1978, 2006) report 500 ft (152 m) of lavas in their "upper andesite sequence" (Tax, their equivalent to the andesite of the Winston graben) on the Chise quadrangle to the east. This thickness is fairly continuous from south to north, but westward the andesite pile thins drastically then pinches out as it crosses the trend of an intrabasinal horst of pre-SFG volcanic rocks referred to here as the Cuchillo Negro uplift (Figs. 2 and 4). The coincidence of the rapid thinning and location of the uplift suggests the horst was topographically high at the time of eruption of the andesite and acted as a topographic barrier to impede westward flow of lava. Alternatively, the extent of the andesite could simply reflect the maximum distance the flows traveled, or could be the result of erosion preferentially thinning the andesite pile only on the west side of the graben. However, the uplift also appears to act as a structural boundary (discussed in more detail below), further suggesting the horst is a significant feature of the graben.

Upper Santa Fe Group

The upper SFG consists of poorly to moderately cemented pebble conglomerates, sandy pebbly conglomerates, and rare very poorly cemented sandstones. It is distinguished from the middle SFG by its poor induration, smaller average gravel size, and shallower bedding angles. Conglomerates consist of poorly to moderately sorted, angular to subrounded, fine to medium pebbles, uncommon coarse pebbles, and rare cobbles of variable clast suites, described below. Conglomerate matrices and sandstones consist of poorly sorted, silty fine to medium sand. Toward the top of the section, buried paleosols are locally common and distinguished by red (hues of 5YR and 2.5YR) horizons. Beds are typically tabular, with rare cross-bedded channels.

Paleocurrents from imbrication measurements (averages of 10-25 individual imbrication measurements at 12 outcrops) indicate that much of the upper SFG was derived from the Black Range (Fig. 2). Clast suites, however, suggest the upper SFG along the east side of the basin was derived from the Sierra Cuchillo. On the west side of the basin, clasts are dominantly rhyolitic with subordinate andesites to subequal rhyolites and andesites, with sparse limestone clasts appearing locally only at the top of the section. To the east, clast suite compositions vary from subequal rhyolites and andesites to andesite-dominated, with up to 20% limestones and sparse red siltstones. In the Winston graben, limestone and siltstone clasts are derived from Paleozoic rocks, which are more commonly exposed in the Sierra Cuchillo (cf., Jahns, 1955; Jahns et al., 2006) than in the northern Black Range (cf., Harrison, 1990). In fact, Paleozoic limestones crop out in the northern Black Range only as small exotic slide blocks surrounded by the andesitic volcaniclastic rocks of the Rubio Peak Formation (Harrison, 1989). Thus, the much greater abundance of limestone clasts in upper SFG strata on the east side of the basin indicates derivation from the Sierra Cuchillo.

On the east side of the graben, the basal contact of the upper SFG is nonconformable on the andesite of the Winston graben, whereas on the west side it is an angular unconformity of about 7 to 15° on the middle SFG unit. The angularity of the unconformity is particularly apparent north of South Fork Creek. South of the Creek, the density of faulting and the spread in individual bedding attitudes increase dramatically, and, combined with the poor exposure, the angularity is less apparent. Here, the contact is placed primarily based on the differing lithologic characteristics of the units (gravel size and degree of induration). The upper SFG unit is correlative to the "Winston beds" (Twc along the west side of the Chise quadrangle) of Jahns et al. (2006).

Boulder-rich Santa Fe Group

At the southwestern corner of the mapped area, the middle-upper SFG division is not clear, as deposits are very poorly exposed and outcrops are similarly consolidated and commonly bouldery throughout. The transition from the pebbly to cobbly middle and upper SFG as described above to the boulder-rich SFG described here is gradational, as the boulder content gradually increases southward. The contact is placed along Monument Creek for convenience, because south of there exposure becomes particularly poor. Deposits are very poorly sorted, with angular to rounded clasts that range in size from fine pebbles up to 2-m-diameter boulders. Consistent pebble imbrications were measured at two outcrops and suggest eastward transport (i.e., from the Black Range), but the distribution of the unit, restricted to the south end of the basin, suggests at least partial derivation from the structurally-high Chise lineament at the south end of the graben. The basal contact is not exposed.

Pliocene(?) pediment and the basalt of Tabletop Mountain

Locally preserved south and north of the area of Figure 2 is a pebbly pediment locally capped in either direction by basalt flows. Gravels of the pediment surface suggest a poorly-sorted, subangular to subrounded, pebble-dominated deposit as much as 4 m thick. Approximately 1 km northeast of Figure 2, the pediment is capped by the basalt of Tabletop Mountain of Harrison (1994), a light gray to black basalt with sparse phenocrysts of olivine, pyroxene, and thin plagioclase lathes. Seager et al. (1984) dated a sample of this flow at 5 Ma by the K-Ar method (Table 1), suggesting a late Miocene or early Pliocene age for the pediment, and placing a minimum age on the end of SFG deposition in the southern Winston graben.

Post-Santa Fe Group alluvium and colluvium

Inset against the SFG strata are five levels of prehistoric, post-SFG alluvium (Qao1, Qao2a, Qao2b, Qao3, and Qay on Figs. 2, 3). These are principally identified on the relative heights of the surfaces capping each deposit, with Qao1 being the highest and oldest and Qay being the lowest and youngest. Rare outcrops suggest that each surface reflects a separate deposit, although Qao2b may be an erosional surface inset upon Qao2a, because they are separated by a small (2-3 m tall) and only locally apparent scarp, with similar sediments on either side. The two units are lumped together as Qao2 where the scarp is not present. As the post-SFG history of the basin is not the focus of this paper, these deposits will only be treated briefly here.

Post-SFG alluvium consists of interbedded cobble beds, pebble beds, pebbly sands, and sands, with finer strata more common in the Qao2 deposits along minor streams and in Qay deposits throughout. Gravels are very poorly to moderately sorted, angular to rounded, and of rhyolitic, andesitic, limestone, and sparse to locally common red siltstone compositions. Matrices are typically silty fine to medium sand, with colors ranging from 5YR 5/3 to 5YR 7/3 in Qao deposits to around 10YR 5/3 in the Qay deposits. Carbonate horizons with development up to Stage III morphology are found in Qao deposits, and up to Stage II in Qay deposits.

Historic and recent alluvial deposits are also present and can be divided into several units based on historic aerial imagery, but are not mapped separately on Figures 2 and 3. Colluvium and minor alluvium that bury important geologic features are locally mapped as Qca on these figures.

STRUCTURE

Bedding Attitudes

In general, bedding attitudes in the Winston graben record progressive fault block tilting through time in the form of progressively steeper dip angles in increasingly older strata (cf. Figs. 2, 3, 4). Mappable angular unconformities exist between the tuff of Little Mineral Creek and the Vicks Peak Tuff, between the middle and upper SFG units, and between the upper SFG unit and the overlying subhorizontal pediment and Pliocene basalt flows. In general, these unconformities are expressions of episodic fault block tilting and concurrent extension (cf., Cather et al., 1994b). The first and oldest probably reflects the initiation of block tilting. The second, which appears to occur just at or after the eruption of the 18 Ma andesite of the Winston graben, may reflect the middle to late Miocene surge in extension rate proposed by Cather et al. (1994b). The final likely reflects cessation of rotation after the late Miocene. No deformation is apparent in sediments inset upon the Pliocene basalts, suggesting the Winston graben has been tectonically inactive since the Pliocene.

In addition to dip magnitudes, dip directions also vary considerably across the southern Winston graben, ranging from west-dipping on the west side of the Cuchillo Negro uplift (CNU) to east-dipping on the east side (Figs. 2 through 4). Along the trend of the uplift, dips are generally northward in the upper SFG, northward to northeastward in middle SFG strata, and north-eastward to eastward in the underlying pre-SFG volcanic rocks composing the CNU itself. This pattern of dip directions suggests the CNU lay near a significant structural boundary within the southern Winston graben that divides the graben into a west-tilted western subbasin and an east-tilted eastern subbasin. The dip directions of foliation attitudes on the CNU itself indicates the uplift is east-tilted as well, though possibly not as strongly as the graben to the east of the uplift. The northward component to the dip direction along the CNU suggests the uplift plunges northward. North of Figure 2, on the Iron Mountain quadrangle, SFG bedding attitudes are subhorizontal (C.T. Cikoski, on-going mapping), and this variability in dip domains is no longer apparent at the surface.

Faulting

Two major faults bound the graben on either side, uplifting Tertiary volcanic rocks, intrusions, and sediments, as well as the older limestones and 'red beds' of the Paleozoic. Intrabasinal faults are also common, particularly at the southern end along the structurally high Chise lineament (Figs. 2, 3). Small displacement (up to 2 m of offset) faults are common in strata as young as the middle SFG unit, and are rare but present in the upper SFG throughout the graben (C.T. Cikoski, on-going mapping). In the basin fill on the Winston quadrangle, fault attitudes are typically north-northwest- to northwest-striking, and dominantly down-to-the-east. Intrabasinal fault offsets are typically small (less than about 300 m), with the exception of the fault system bounding the CNU (Adams and Chihenne faults on Fig. 2), which juxtaposes middle SFG sediments against late Oligocene volcanic rocks. Fault planes are mostly steeply dipping (55 to 80°), though the down-to-the-west Adams fault locally dips as shallowly as 44° (Fig. 3). Down-to-the-west faults are not common to the area of Figure 2, but may be common but more difficult to identify east of the CNU. In half-graben basins, bedding dip directions and dominant fault dip directions are typically opposing, as seen on the west side of the CNU with bedding dip directions to the west and fault dip directions to the east. As the basin east of the CNU typically has eastward bedding dips, west-dipping fault planes are expected to be more common on this side of the basin. Poor exposure, discontinuous beds, and the general monotony of the andesite of the Winston graben may inhibit recognition of down-to-the-west faults in this east-tilted domain.

It is often said in the literature that the pediment and basalt flows capping the SFG in the Winston graben are not offset by the basin-bounding faults (Jahns, 1955; Harrison, 1990, 1994). D.J. Koning (pers. comm.), however, found low, degraded scarps in the pediment to the north of this study area at the point where the pediment crosses the graben-bounding faults. In addition, C.T. Cikoski and D.J. Koning each observed a small outcrop of basalt elevated approximately 4 m above the main basalt flow capping Tabletop Mountain on its east end, which we interpret as the result of post-depositional fault slip along the eastern graben-bounding fault. We therefore suggest that some offset did occur along the basin-bounding faults since the development of the pediment and emplacement of the basalt flows, but it has likely been minor and possibly no more than 4 m of offset.

DISCUSSION AND CONCLUSIONS

The angular unconformity at the base of the Vicks Peak Tuff suggests that surface tilting related to crustal extension and graben subsidence began as early as 29 Ma. Working primarily in the Black Range, Harrison (1990, 1994) suggests the main fault trend during this time period was northwest-southeast striking, based on the attitudes of veins and mineralized fault zones with vein adularia that were K-Ar dated to 26.2 to 28.9 Ma (ages from M. Bauman, unpubl. report, cited in Harrison, 1986). Harrison (1990) noted that these faults are typically high angle with both normal and oblique slip vectors, and generally have offsets of less than a few hundred meters. These faults may have influenced the paleodrainage pattern of the area, as the paleocurrent indicators in the lower SFG unit indicate southeastward paleoflow, parallel to the strike of these late Oligocene faults. Fault activity may have formed strike valleys that subsequently captured and directed stream flow. This control on flow pattern may explain why the Vicks Peak Tuff was only locally stripped from the area before deposition of the lower SFG, as the streams would not necessarily be able to meander outside of their respective strike valleys. Direct evidence of this relationship is lacking, however. The erosive nature of the contact between the lower SFG and the Vicks Peak Tuff suggests that accommodation space associated with initial graben subsidence was minor, as significant accommodation space would promote burial and preservation of the Vicks Peak Tuff, not incision into and removal of the tuff. This is consistent with the relatively small fault offsets observed by Harrison (1990) for the mineralized northwest-striking late Oligocene faults in the Black Range.

In the middle SFG unit, paleocurrent indicators suggest drainage was directly eastward on the west side of the basin and westward on the east side, with the paleostreams meeting in the present-day area of Chloride and Cuchillo Negro Creeks and flowing southward from there. This indicates that both the Black Range and Sierra Cuchillo highlands were elevated by this time, and suggests that the CNU was not a major topographic high for at least early middle SFG time. Facies distributions corroborate this suggested drainage pattern, as pebbles and cobbles dominate middle SFG strata on the east and west sides of the graben, fine-grained sandstones and siltstones dominate the axis, and mudstones are found at the southern end of the graben, possibly reflecting the presence of a lake or playa at the terminus of the drainage network at the south end. This, in turn, is consistent with the model proposed by Bowie and Barker (1986) to explain the zeolitization of the lower SFG and tuff of Little Mineral Creek around the St. Cloud open pits, which relies on the presence of a saline lake in that area to cause alteration. Thick sections of mudstones were not found, however, and any remains of the main body of the lake were likely removed by late Cenozoic erosion along South Fork and Cuchillo Negro Creeks.

The middle SFG is capped by the andesite of the Winston graben on the east side of the CNU and by an angular unconformity on the west side. The andesite thins from east to west, particularly where crossing the trend of the CNU, pinching out just west of the trend. It is possible that the CNU controlled the distribution of the andesite by acting as a topographic barrier, which would place a minimum age on the rise of the CNU at 18 Ma. Given that a few flows of andesite are found along and west of the CNU trend, the andesite may have on-lapped and buried the uplift before eruption ceased.

While the Winston graben is typically described as a symmetrical graben, the westward dips west of the CNU and eastward dips on and to the east of the CNU indicate tilting of strata in opposing directions on the west and east sides of the basin, suggesting the southern Winston graben may have behaved at least in part as two asymmetric half-graben of opposing polarity (cf., Fig. 4). The divide between the two polarities of tilting appears to lay near the Adams fault on the west side of the CNU, where comparatively low dip magnitudes and high variability in dip directions are found in the middle SFG and Oligocene volcanic strata exposed at the surface (Fig. 2). The exact location of the divide may have moved through time, as although the oldest strata on the CNU are eastward dipping, the upper SFG strata found along the CNU trend are northward dipping. This is perhaps the result of the CNU tilting eastward with the eastern side of the basin early in the history of the basin, but subsequently behaving more independently. North of Figure 2, subhorizontal upper SFG strata dominate the surface, and here the Winston graben appears to be symmetrical. At present, it is not known whether the shift from dual asymmetric half-graben to a single symmetrical graben is temporal (i.e., the two half-graben merge through time) or spatial (the asymmetry decreases northward, resulting in a symmetrical northern Winston graben).

In the southwest corner of the Winston graben, westward dips throughout the upper SFG (Fig. 2) indicates that fault block tilting continued well into upper SFG time. The pediment and local Pliocene basalts capping the SFG show no clear evidence of tilting, but small offsets of the pediment (D.J. Koning, pers. comm.) and the basalt capping Tabletop Mountain (Cikoski and Koning, unpublished data) along the basin-bounding faults indicate that minor fault slip did continue into the Pliocene. No deformation is apparent in any inset post-SFG alluvial deposits, suggesting no fault activity of great enough magnitude to affect the surface has occurred in the Winston graben since the Pliocene.

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