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STRATIGRAPHY OF THE NORTHWESTERN SIERRA BLANCA VOLCANIC FIELD

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ABSTRACT—A thick succession of 28–38 Ma alkalic lava flows, volcaniclastic sedimentary deposits, and minor welded trachytic ash-flow tuffs is preserved in the northwestern Sierra Blanca volcanic field (SBVF) on the western flank of the Sierra Blanca massif, on Barber Ridge, and in the Godfrey Hills. Here, we present a stratigraphic framework for this succession based on geologic mapping, geochronology, and geochemistry. Three sequences of volcanic rocks are preserved on the Sierra Blanca massif. The 38 to 36 Ma lower sequence is composed of three units that are relatively continuous (listed from bottom to top): interbedded debris flows and pyroxene-phyric basalt to basaltic trachyandesite flow breccias and lava flows (Hog Pen Formation), plagioclase-phyric basaltic trachyandesite flows (Rattlesnake Member of the Three Rivers Formation), and fine-grained trachybasalt to trachyte flows interbedded with maroon volcaniclastic sediment (Taylor Windmill Member of the Three Rivers Formation). The northward-thickening, 36 Ma rheomorphic Argentina Spring Tuff caps the lowest sequence. The middle sequence consists of laterally discontinuous volcaniclastic debris flows, basaltic trachyandesite, phonotephrite, and trachyte of variable thickness (Double Diamond Member of the Three Rivers Formation, 36–34 Ma). The highest sequence on the Sierra Blanca massif is composed of thick, biotite- and potassium feldspar-bearing, 33–31 Ma flows filling paleovalleys cut into the older lavas. Volcanic rocks on Barber Ridge between Sierra Blanca and the Godfrey Hills are composed exclusively of the 38–37 Ma debris flows and pyroxene-phyric flow-breccias and lavas of the Hog Pen Formation. The Godfrey Hills, on the hanging wall of the north-striking, west-dipping Godfrey Hills normal fault, preserve the younger part of the volcanic succession of the SBVF. The oldest units in the Godfrey Hills are distal equivalents of the Hog Pen Formation, and the Rattlesnake Canyon and Taylor Windmill members of the Three Rivers Formation on Sierra Blanca. A thin lithic-rich tuff with biotite and brown porphyritic clots, the Buck Pasture Tuff, lies above the Taylor Windmill Member; this tuff may correlate with a similar tuff above the Argentina Springs Tuff on Sierra Blanca. The upper succession in the Godfrey Hills is divided into two units, the older (34 to 28.7 Ma) Lopez Spring Formation with lavas of variable composition and the younger Husk Windmill (28.7–28.2 Ma) Formation dominated by trachytic lava and tuff. The northwestern SBVF primarily formed during two widespread pulses of volcanic activity at 38–34 Ma and 29.4 -28.2 Ma and a more localized episode 33–31 Ma. The youngest volcanic rocks dated so far in the northwestern SBVF were erupted at ca. 28.2 Ma; the youngest sill is ~27 Ma.

INTRODUCTION

The Sierra Blanca volcanic field (SBVF) in south-central New Mexico is located at the transition between the tectonically stable High Plains and the tectonically active western United States (Fig. 1). Like many volcanic fields within the Great Plains alkaline province, located to the north and south along this fundamental boundary in the North American plate, this volcanic field provides important clues about the state of the mantle and the crust during the time that the subducting Farallon plate began to founder, as discussed by Moore et al. (1991). Furthermore, the SBVF developed during the time interval encompassing the gradual structural shift from Laramide compressional and strike-slip deformation to Rio Grande rift extension, providing a good record of when and how the transition proceeded in this area, as described in detail by Koning et al. (this volume). The SBVF is within the Sierra Blanca Basin, a north-northeast trending Laramide to post-Laramide basin (Koning et al., this volume) that lies on the northeastern margin of the Tularosa Basin, a significant Oligocene to Miocene basin that formed during Rio Grande rift extension (e.g., Seager et al., 1984; Orr and Myers, 1986).

Starting in 2007, a team of geologists associated with the New Mexico Bureau of Geology and Mineral Resources mapped the northwest side of the Sierra Blanca massif. This mapping extended to the northeastern border of the Tularosa Basin between Tularosa to the south and Carrizozo to the north, including both Barber Ridge and the Godfrey Hills located west of Sierra Blanca (Fig. 1). During the course of the 1:24,000 scale mapping, we came to recognize several distinct, mappable volcanic and plutonic units exposed on the western and northern margins of the Sierra Blanca massif, on Barber Ridge, and in the Godfrey Hills in the northwestern part of the SBVF (Fig. 1). This paper summarizes refinements to the stratigraphy developed by Thompson (1972) for the lava flows and volcaniclastic deposits in this area. The plutonic rocks of the Three Rivers Stock are discussed by Goff et al. (this volume). This refined stratigraphic framework captures the episodic nature and compositional changes of the volcanism through time in this area.

Appendix data for this paper can be accessed at:
http://nmgs.nmt.edu/repository/index.cfm?rid=2014002

PREVIOUS WORK

Thompson (1964, 1966, 1972, 1973) divided the volcanic rocks of the northwestern SBVF into four formations (listed oldest to youngest): Walker Andesite Breccia, Nogal Peak Trachyte, Church Mountain Latite, and Godfrey Hills Trachyte. Thompson (1964) measured ~1020 m of volcanic rocks along two section lines on the west side of the volcanic field between the ridge on the north side of Elder Canyon and the top of Nogal Peak (Figs. 1, 2). Thompson recognized 41 volcanic units along this composite section, 36 of which were later assigned to the Walker Andesite Breccia (Thompson, 1972; Fig. 2). Although most of the units are

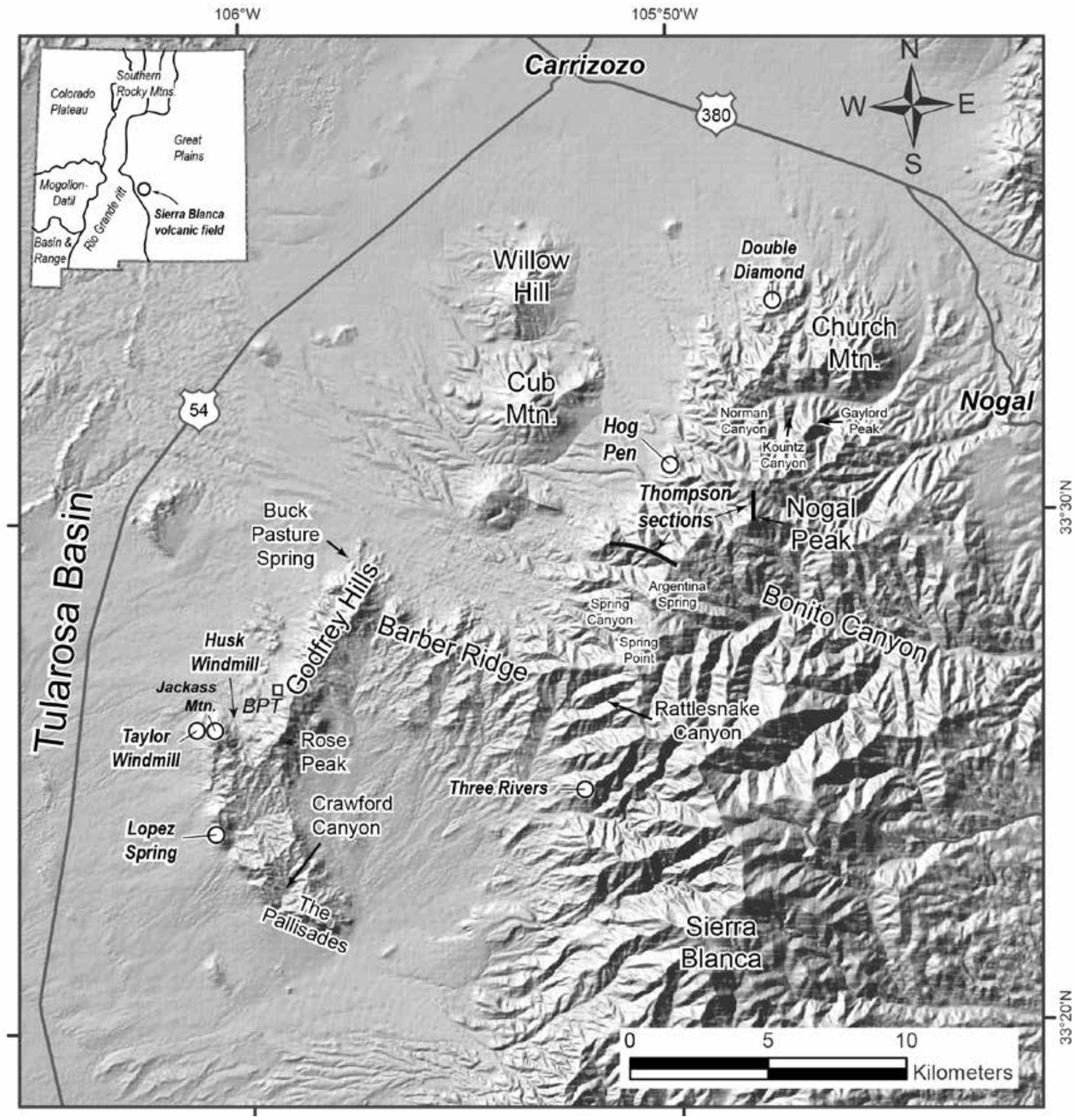

FIGURE 1. Hillshade index map of the northwestern part of the Sierra Blanca volcanic field showing the stratigraphic type sections of our proposed units (white circles) and geographic features discussed in the text. The approximate location of the idealized section presented in Thompson (1973) is depicted by the black line segments. The white box labeled BPT (Buck Pasture Tuff) highlights the location of exceptional exposures of this unit.

described as "andesite porphyry" and "andesite breccia," he did identify a few distinctive units, including a hornblende-bearing "andesite porphyry" (unit 2) and a tuff with abundant plagioclase laths (unit 18; Fig. 2). Three thick "andesite" flows near the top of the sequence (units 30, 32, and 34) can be traced for a few km along the western escarpment of Sierra Blanca. Thompson (1964) described the Nogal Peak unit near the top of the section as a porphyritic hornblende andesite. He also discussed the striking lack of topographic relief on the flows between eruptions and the general continuity of lava flows in certain parts of the measured section.

Through the years, Thompson made additional observations about the stratigraphy of the northwestern SBVF. Thompson (1972, 1973) noted an up-section decrease in pyroxene and an up-section increase of hornblende, sanidine, and biotite. He more clearly defined the Nogal Peak Trachyte to consist of five units with a total preserved thickness of 300 m, including two fragmental units displaying a "…fluidal structure around the phenocrysts and fragments" that are separated by a volcaniclastic interval (Thompson, 1973, p. 6; units 37 and 38, Fig. 2). He defined the ~230 m-thick Church Mountain Latite, which consists of lava flows and ash flow tuffs containing sanidine and hornblende phenocrysts that are embayed or replaced; flow-banding is a common texture in the tuffs (Thompson, 1973). The Church Mountain Latite has a K-Ar age of 31.8 ±1.3 Ma (Thompson, 1972; adjusted to 32.0 Ma, see methods section below). Both Thompson (1973) and Weber (1964) recognized the similarity of the lava flows on Church Mountain and on Gaylord Peak (Fig. 1) in the northern part of the field. Finally, Thompson (1972) applied the name the Godfrey Hills Trachyte to the 180 to 550 m thick succession of lava flows, tuffs, and volcaniclastic sediments overlying the Walker Andesite

Breccia in the Godfrey Hills. A flow near the base of the unit yielded a K-Ar age of 26.1 ±1.1 Ma (Thompson, 1972, 26.2 Ma adjusted value).

The southern part of the volcanic field on the Mescalero Apache Reservation was mapped and described by Moore et al. (1988a, 1988b, 1991) and Allen and Foord (1991). Although no formal stratigraphy was proposed, Moore et al. (1991) did recognize spatial patterns and general chemical trends through the evolution of the volcanic pile, particularly upward enrichment of both silica and alkalis. These authors point out that, generally, trachybasalt, trachyandesite, tephriphonolite (i.e., alkalic trachyandesite, see Figure 3 for volcanic rock classification) and trachyte flows intercalated with volcaniclastic sedimentary rocks are exposed in the northern part of the field. In contrast, more alkalic lavas, including phonolite porphyry flows, trachyte and phonotephritic flow breccias, and trachybasalt flows interbedded with volcaniclastic sedimentary rocks are exposed in the southern part of the field. The southern extremely alkali-rich lavas interfinger with the northern alkaline lavas in the central and northern parts of the field in the vicinity of Three Rivers Canyon (Fig. 1; Moore et al., 1991). Like Thompson (1973), Moore et al. (1991) noted the decrease of pyroxene and olivine and the increase of biotite up-section in the northern part of the field. Moore et al. (1988a, 1988b) mapped three generalized volcanic units in the southern part of the field (oldest to youngest): (1) trachyte flows, phonotephritic flow breccias, and minor ash flow tuff; (2) porphyritic phonolite flows; (3) trachybasalt flows. According to the correlation charts on these maps, some of the trachybasalt flows are older than the porphyritic phonolite flows. The age of the base of the volcanic succession postdates 37.3–37.8 Ma (adjusted ages 37.5–38.0 Ma), the age of intrusions below the lavas (Allen and Foord, 1991). Uppermost trachyphonolite flows are cross-cut by a 37.0 Ma (adjusted to 37.2 Ma) nepheline syenite intrusion near Sierra Blanca Peak, providing a minimum age constraint for preserved lavas in the southernmost part of the volcanic field (Allen and Foord; 1991). Thus, two pulses of volcanism were documented by previous workers, one at 38–37 Ma (Allen and Foord, 1991) and a poorly constrained episode at 30 to 26.2 Ma (Thompson, 1972).

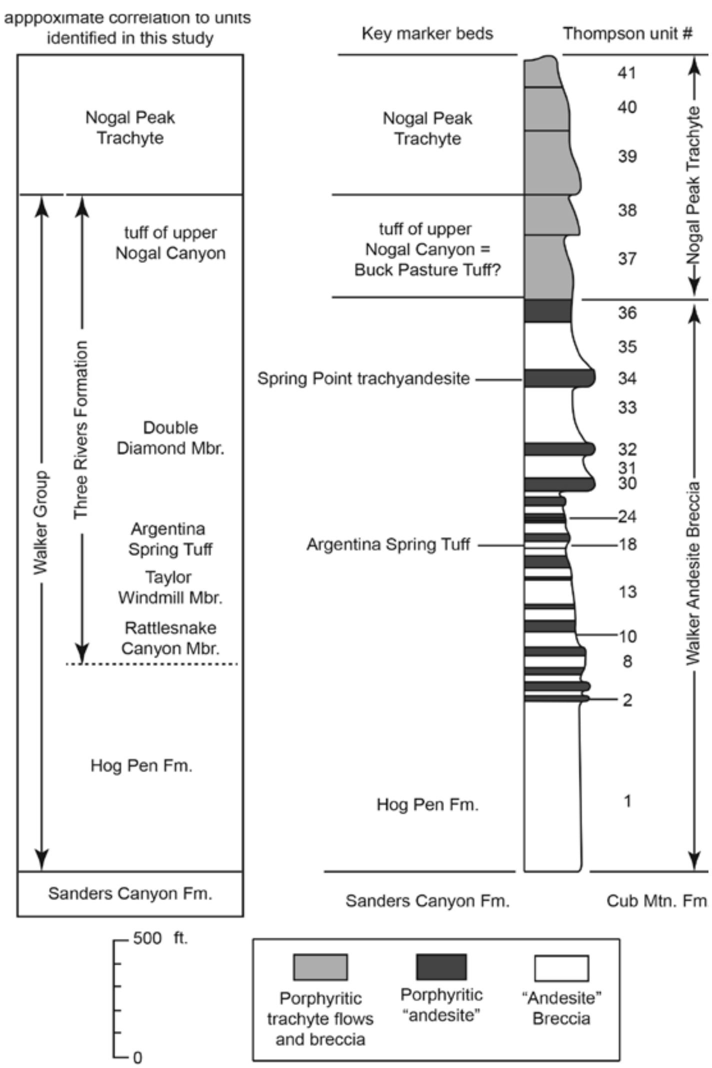

FIGURE 2. The right-hand column presents the stratigraphic column published by Thompson (1973). The middle column shows key beds that we easily correlate to our proposed stratigraphy. The left-hand column illustrates our best attempt of correlating our proposed stratigraphy to that of Thompson (1964, 1973).

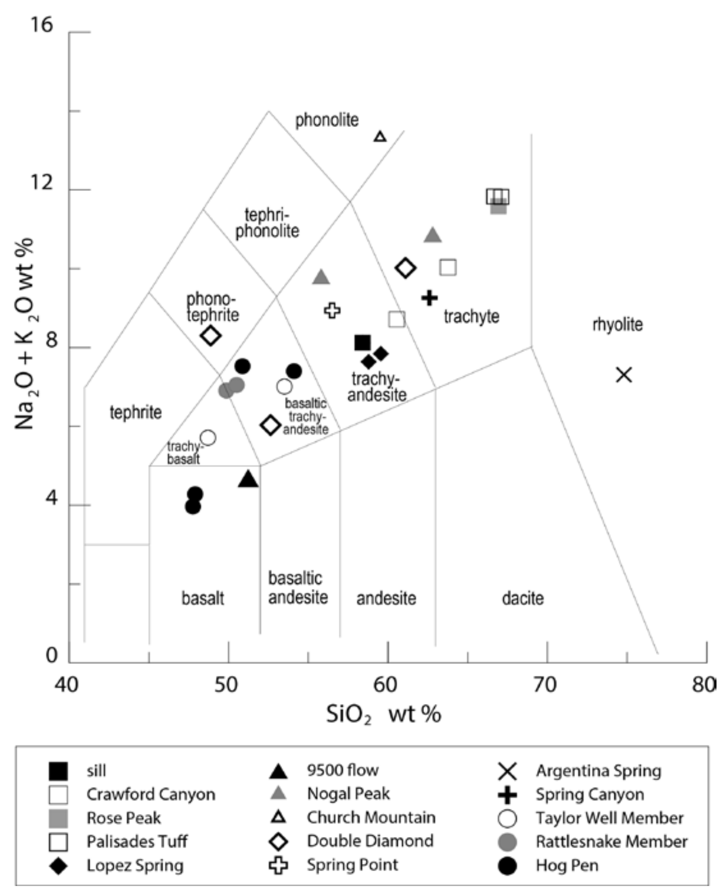

FIGURE 3. Total alkali versus silica diagram showing the geochemistry of samples collected during this study keyed to stratigraphic unit. The IUGS classification of volcanic rocks (after LeBas et al., 1986) is plotted for reference.

METHODS

Here we divide the "Walker Andesite Breccia" of Thompson (1964, 1972) into several compositionally distinct flow sequences separated by gradational boundaries. We use a combination of geologic mapping, geochronology, and geochemistry to develop a revised stratigraphic framework for the volcanic rocks in the northwestern part of the volcanic field between the Godfrey Hills on the west, Church Mountain to the north, and the village of Nogal and Ski Apache on Sierra Blanca to the east. As the formulation of the stratigraphy progressed, we identified areas with good exposures on public land as type sections to facilitate future study of these volcanic rocks.

Geochronology

The new $^{40}Ar/^{39}Ar$ dates reported here were determined at the New Mexico Geochronology Research Laboratory using methods similar to those described in McIntosh and Chapin (2004). An age of 28.02 Ma for the Fish Canyon Tuff (Renne et al., 1998) was used in age calibration and to adjust previously published dates (the adjustment involves multiplying the old values by 1.006). Ages of twelve lava flows, six tuffs, two sanidine-bearing dikes, a sill, and a biotite-bearing dacite cobble from a volcaniclastic unit are presented to constrain timing within the stratigraphic framework. Many more samples were submitted for analysis, but quite a number of rock units could not be dated because of alteration and lack of datable phases. Successful dates from samples from other intrusions gathered during this study are presented in companion papers (Goff et al., this guidebook; Koning et al., this guidebook). Several of the dates from the lava flows are incremental-heating plateau ages for biotite and hornblende phenocrysts and for groundmass concentrates from rocks lacking datable phenocryst phases. Sanidine-bearing tuffs, lavas, and dikes were dated using single-crystal, laser analysis. Analytical uncertainties for individual samples are reported to two standard deviations (95% confidence level). Detailed procedures are described in Appendix 1 in the NMGS data repository. The new dates most pertinent to this investigation are summarized in Table 1, which is organized temporally from youngest to oldest. The analytical age data, age spectra, quality of the analyses, and probability plots are also available in Appendix 1.

Geochemistry

Most of the rock names assigned during mapping were based on hand lens or thin section identification of visible phenocrysts. Chemical analyses were acquired for key units in the succession so that proper rock names based on a total alkali versus silica plot (LeBas et al., 1986) could be applied to the stratigraphic framework. Geochemical samples were broken into coarse chips with rock hammer and 240 g of clean chips with no weathered surfaces were sent to ALS Laboratory Group in Reno, Nevada. Major elements in the samples were measured using lithium borate fusion of the sample prior to acid dissolution, followed by analysis using both an ICP-AES and ICP-MS (ALS's process CCP-PKG01). Carbon and sulfur were determined using a combustion furnace. Three types of digestion were used in trace element analysis: a lithium borate fusion for the resistive elements, a four acid digestion for the base metals, and an aqua regia digestion for the volatile gold-related trace elements. Trace elements, including the full rare earth element suites, were measured using either an ICP-AES or ICP-MS. The results are available in Appendix 2 in the NMGS data repository and are plotted in Figure 3.

Measured sections

Stratigraphic type sections were measured using a Jacob staff, Brunton compass, and hand-held GPS units. For each of the type sections, units were described in detail at the time of measurement and, for many sections, hand samples were taken from each unit. The hand samples were examined under a binocular microscope and additional details noted. Exact locations, detailed descriptions, and graphical presentations are archived in Appendix 3. The geographic names and positions of the units within the stratigraphy can be found in Figures 1, 2, and 4 and will be described in detail in the next section.

The type section for the oldest volcanic unit in the SBVF, the Hog Pen section, is located in a small drainage just west of Water Canyon Campground on the western escarpment of the Sierra Blanca massif, 15 km southeast of Carrizozo. The name of this unit, the Hog Pen Formation, is derived from Hog Pen Canyon located just north of the measured section (Fig. 1). The base of the section is located near the trail into Water Canyon and is in the Lincoln National Forest.

The Hog Pen Formation and the overlying Three Rivers Formation are well exposed on a ridge northeast of the Three Rivers Campground, located between Three Rivers Canyon and Dry Canyon along the western escarpment of the Sierra Blanca massif. The base and the top of the section are located near trails and are in the Lincoln National Forest. The name of the unit above the Hog Pen Formation, the Rattlesnake Canyon Member of the Three Rivers Formation, comes from Rattlesnake Canyon located to the northwest of the section line (Fig. 1).

A thinned succession of Hog Pen Formation and the Rattlesnake Member of the Three Rivers Formation are present on the west side of the Godfrey Hills in an arroyo 2.3 km northeast of Taylor Windmill on BLM property. The type section for the overlying unit, herein named the Taylor Windmill Member of the Three Rivers Formation, is located to the east of the arroyo. The section measured near Taylor Windmill includes the Hog Pen Formation, all three members of the Three Rivers Formation, and the Buck Pasture Tuff (Appendix 3). The Buck Pasture Tuff is named for exposures of this unit near a spring at the north end of the Godfrey Hills (Fig. 1).

A small drainage just north of Lopez Spring on the west side of the Godfrey Hills exposes the type section for the Lopez Spring Formation, which overlies the Buck Pasture Tuff. The type section for the youngest part of the sequence in the SBVF is on Jackass Mountain on the west side of the Godfrey Hills and is named for nearby Husk Windmill. The Palisades Tuff, the Rose Peak Trachyte, and the Crawford Canyon Trachyte exposed in

TABLE 1. $^{40}Ar/^{39}Ar$ dates of volcanic rocks in the northwestern Sierra Blanca volcanic field

Sample	Field #	General location	Rock Type	Stratigraphic Position	Easting[1]	Northing	Age (Ma)	Error (Ma)	Phase	Dated quality
VOLCANIC ROCKS										
1	08GD19a	Crawford Spring Golondrina Draw quadrangle	vitric lithic tuff	interbedded with volcaniclastic sediments in a faulted area	409692	3692960	28.23	0.06	sanidine	good
2	11OS03	Jackass Mountain Oscura quadrangle	ashy biotite trachyte	within Crawford Canyon Trachyte	406136	3698164	28.6	0.05	sanidine	noisy
3	08GD22	Crawford Canyon Golondrina Draw quadrangle	Rose Peak trachyte	just above Palisades Tuff	408022	3693168	28.59	0.05	sanidine	good
4	10GP10	Rose Peak Godfrey Peak quadrangle	Rose Peak trachyte	dike north of the Jackass Mtn. fault	407283	3698623	28.53	0.03	sanidine	good
5	11GP29	S of Halfway Windmill Godfrey Peak quadrangle	block of Palisades Tuff	clast in highest volcaniclastic unit	408967	3694496	28.55	0.1	sanidine	fair
6	08GD23	Crawford Canyon Golondrina Draw quadrangle	Palisades Tuff	Palisades Tuff	407984	3693115	28.67	0.07	sanidine	good
7	09GP25	Rock Point Spring Godfrey Peak quadrangle	Palisades Tuff	Palisades Tuff	409947	3704253	28.66	0.08	sanidine	fair
8	11GP42	Rose Peak Godfrey Peak quadrangle	biotite trachyte	immediately below Palisades Tuff	408617	3700910	28.78	0.04	sanidine	noisy
9	O-2	Lopez Spring Oscura quadrangle	biotite trachyte cobble in volcaniclastic sediment	Between the Buck Pasture and Palisades tuffs	405724	3695342	30.04	0.2	biotite	poor
10	10CM1	headwaters of Normal Cany. Church Mountain quad-rangle	biotite trachyte	above the tuff of upper Nogal Canyon	426032	3707919	31.41	0.38	gm	poor
11	08GD20	Crawford Canyon Golondrina Draw quadrangle	trachyte	below Palisades Tuff in southern Godfrey Hills	407815	3692804	31.05	0.76	gm	poor
12	CMC82	Church Mountain Church Mountain quad-rangle	phonolite	Church Mountain Phonolite near base	426779	3712104	32.7	0.1	sanidine	good
12	CMC82	Church Mountain Church Mountain quad-rangle	phonolite	Church Mountain Phonolite near base	426779	3712104	32.95	0.12	biotite	good
13	CMC83	Church Mountain Church Mountain quad-rangle	phonolite	Church Mountain Phonolite	429509	3712021	32.71	0.13	biotite	good
14	11GP43	Rose Peak Godfrey Peak quadrangle	Buck Pasture Tuff	Buck Pasture Tuff	408270	3700988	34.28	0.05	sanidine	noisy
15	F10-40	Spring Point Nogal Peak quadrangle	trachyandesite	overlies Argentina Spring Tuff	421566	3702246	35.32	0.16	gm	good
16	10NP3	Sanders Ridge Nogal Peak quadrangle	Argentina Spring Tuff	Argentina Spring Tuff	422140	3705226	36.06	0.7	gm	poor
17	F10-43	Spring Canyon Nogal Peak quadrangle	trachydacite	underlies Argentina Spring Tuff	421692	3703328	36.87	0.13	gm	good
18	10NP1	Sanders Canyon Nogal Peak quadrangle	trachybasalt	in Taylor Well Fm. just above contact with Hog Pen	421220	3706659	37.84	0.48	gm	poor
19	Tu-1635	west side of northern God-frey Hills, Oscura quad-rangle	biotite and hnd-bearing trachyte	lower Hog Pen Fm.	406583	3701389	36.57	0.21	hb	fair
20	11GP7	Barber Ridge Godfrey Peak quadrangle	trachybasalt with pyroxene and horn-blende xenoliths	lower Hog Pen Fm.	411731	3700690	37.01	0.1	hb	fair
DIKES										
21	11GP40	north of Halfway Windmill Godfrey Peak quadrangle	sanidine-bearing trachyte	dike cutting Crawford Canyon Trachyte	407776	3697345	28.57	0.08	sanidine	fair
22	10GP22	Rose Peak Godfrey Peak quadrangle	sanidine-bearing trachyte	cuts Palisades Tuff	408846	3698785	17.91-29.3		sanidine	com-plex
23	08GD31	Southern Godfrey Hills Golondrina Draw	equigranular sill with orthoclase and horn-blende	appears to intrude Hog Pen Fm.	407944	3690593	27.05	0.81	gm	fair

hb=hornblende; gm=groundmass
1. UTM locations NAD27, zone 13.

this type section are named for geographic localities containing good exposures of these units (Fig. 1). Both of these type sections are located on BLM property.

The final type section is located at the northern end of the Sierra Blanca massif. Here we define a type section for a unit that is stratigraphically above the Taylor Windmill Member of the Three Rivers Formation and stratigraphically below a pair of tuffs tentatively correlated to the Buck Pasture Tuff. This unit is named the Double Diamond Member of the Three Rivers Formation for exposures on Double Diamond Peak (Fig. 1). The type section is in Lincoln National Forest.

REVISED STRATIGRAPHY

Overview: Sierra Blanca Massif

Here we use field-based observations and $^{40}Ar/^{39}Ar$ dates determined during this study to revise the stratigraphy of the northwestern SBVF. Figure 2 illustrates the units measured by Thompson (1964, 1973) and the proposed new stratigraphy on the Sierra Blanca massif near Nogal Peak. Figure 4 depicts the revised stratigraphy on the Sierra Blanca massif and the projection of the units north into the Church Mountain area and west to Barber Ridge and the Godfrey Hills. Table 2 highlights the distinguishing features of each volcanic rock unit that can be identified in the field using a hand lens. We formally propose raising the Walker Andesite Breccia to group status (Walker Group) because the unit clearly contains rocks other than breccia and the volcanic rocks are more alkalic than andesite (Figs. 2–4). We divide the Walker Group into two formations that capture the geochemical evolution of the volcanic field through time (Figs. 2–4). The oldest unit exposed in the northwestern SBVF, the Hog Pen Formation, is overlain by the Three Rivers Formation, which consists of (from oldest to youngest): the Rattlesnake Canyon, Taylor Windmill, Argentina Spring Tuff, Double Diamond, and Buck Pasture Tuff /tuff of upper Nogal Canyon members. The contacts between all the formations and members of the Walker Group are gradational in most sections. The thickness of the Hog Pen Formation ranges from 350 to >550 m, with the greatest thickness at Barber Ridge. The Three Rivers Formation below the Double Diamond Member is 300 to 700 m thick, thickening toward the east. The Double Diamond Member is 100 to 200 m thick.

The name of the Nogal Peak Trachyte (Thompson, 1964) remains unchanged but the terminology is extended to include trachyte flows capping ridges to the north of Nogal Peak. In addition, units 37 and 38 of Thompson (1964, 1973), which are clearly tuffs, are removed from the Nogal Peak Trachyte and assigned to the tuff of upper Nogal Canyon. The Church Mountain "Latite" of Thompson (1964, 1973) is herein modified to Church Mountain Phonolite, based on the rock chemistry of the unit determined during this investigation (Figure 3).

Overview: Godfrey Hills

The Godfrey Hills expose both the older and the younger parts of the volcanic succession of the northwestern SBVF. The oldest units in the Godfrey Hills are distal equivalents of the pyroxene-phyric, the plagioclase-phyric, and the crystal-poor mafic flows on Sierra Blanca (Hog Pen Formation and the Rattlesnake Canyon and Taylor Windmill members of the Three Rivers Formation, Fig. 4). These older flows are overlain by the lithic-rich Buck Pasture Tuff with angular fragments of older, dark-colored lava rocks, abundant fiamme, and decimeter-scale blobs of brown, flattened lava with about 5–15% plagioclase, sanidine, and biotite. This tuff may correlate with the tuff of upper Nogal Canyon on the Sierra Blanca massif.

The Godfrey Hills "Trachyte" of Thompson (1964, 1973) is made up of (from oldest to youngest): (1) an interval containing a few thin, discontinuous trachyandesite and trachyte flows and a thick aphyric trachyandesite that is dominated by volcaniclastic sedimentary deposits, (2) a discontinuous, thick biotite-hornblende trachyte, (3) a welded ash flow tuff of trachytic composition, (4) a sparsely porphyritic trachyte with

TABLE 2. Diagnostic field characteristics of the volcanic units in the northwestern SBVF

Stratigraphic name	% Phenocrysts	Phenocryst size	Definitive phenocryst	Main rock type	Other features
Hog Pen Fm.	15–20	up to 5 cm, most 3–4 mm	pyroxene	debris flows; lava and flow breccia	greenish-gray color
Three Rivers Fm.					
Rattlesnake Canyon	10–30	up to 2.5 cm, most 2–4 mm	plagioclase	lava flows	""turkey-track"" flows near base and top
Taylor Windmill	<2	<2 mm	plagicoclase	speckled lava flows	deeply altered, red vs
Argentina Spring	5–15	3–5 mm	plagioclase	rheomorphic tuff	fluidal texture
Double Diamond	5–15	3–5 mm	amphibole	lava flows	K-spar
Buck Pasture	5–15	2–4 mm	sanidine	5–10% lithic tuff	brown clots, sometimes rheomorphic
Lopez Spring	variable	variable	biotite/hnd in vs	subequal lava flows and vs	variable
Husk Windmill					
unnamed trachyte	5–15	2–4 mm	biotite/hnd	lava	gray color
Palisades Tuff	5–10	2–4 mm	sanidine	lithic-poor tuff	flatten fiamme
Rose Peak	7–10	3–6 mm	sanidine	subequal lava and block-and-ash	lava is gray, block- and-ash is orange
Crawford Canyon	<1	<2 mm	plagioclase	lava flows	elongated vesicles

hnd = hornblende; K-spar = potassium feldspar; vs=volcaniclastic sedimentary deposits

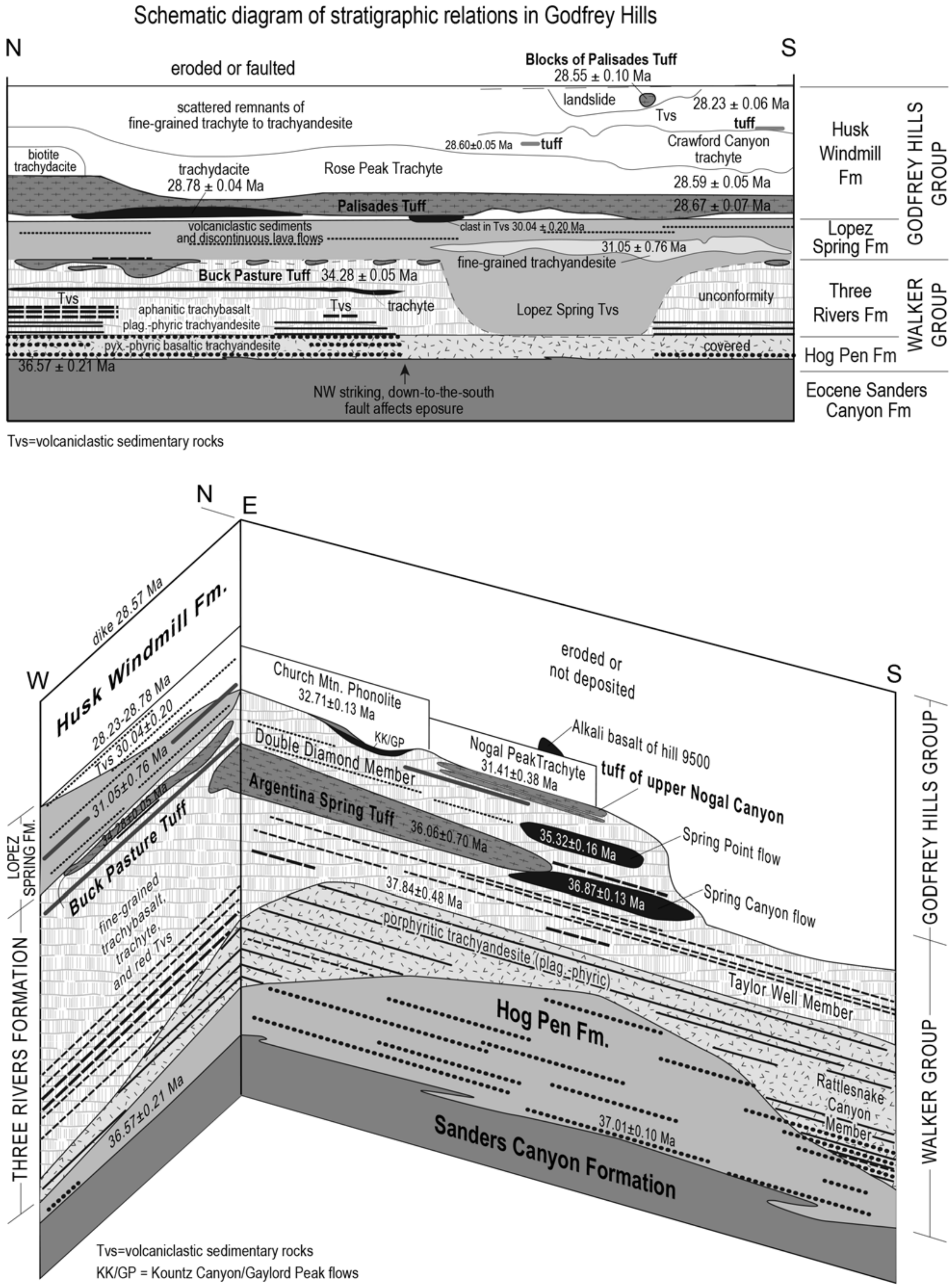

FIGURE 4. Schematic fence diagram showing the stratigraphic relations among the volcanic units on Sierra Blanca and in the Godfrey Hills. Thickness is not to scale. (See also Color Plate 8)

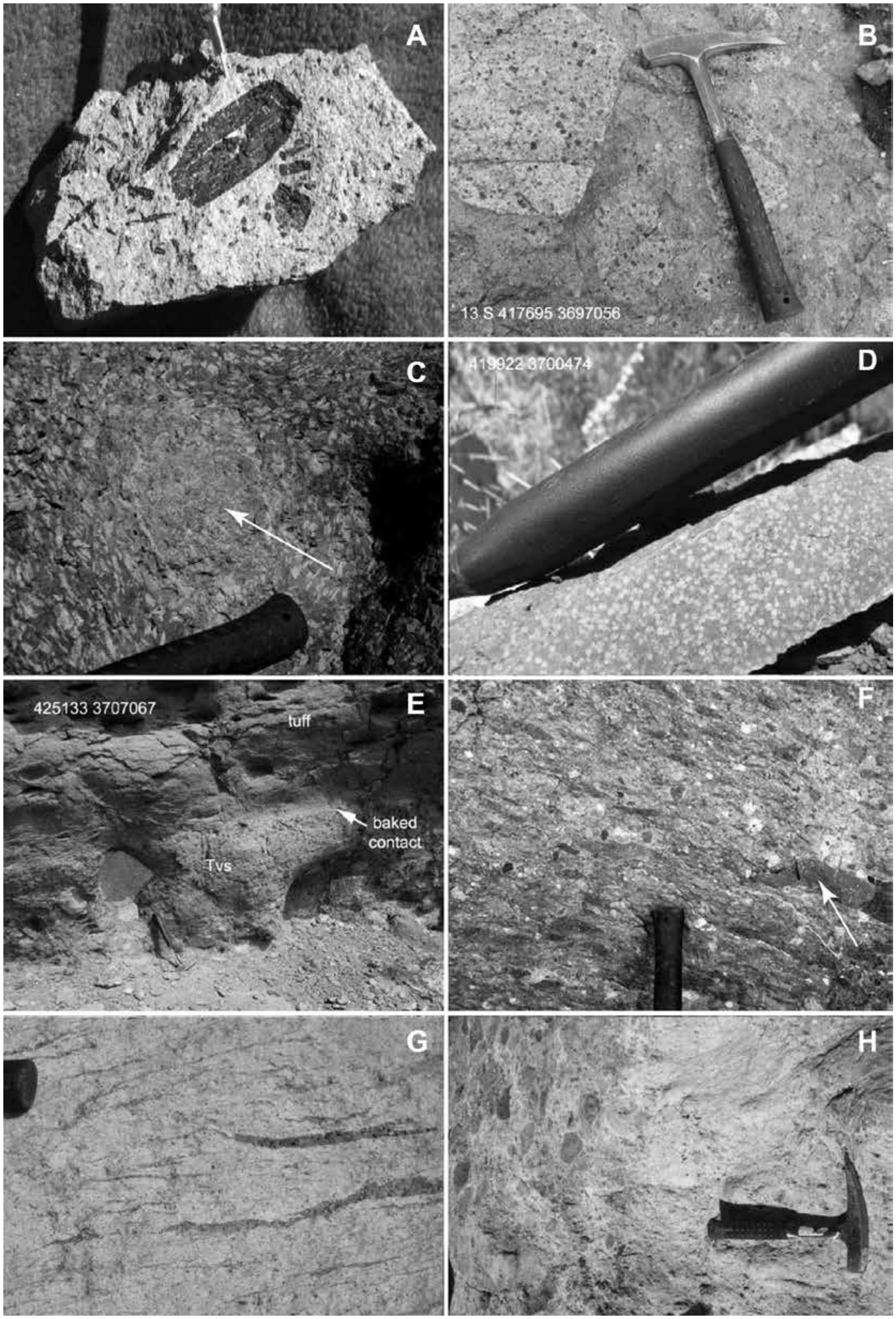

FIGURE 5. Photographs of some of the distinctive volcanic units in the northwestern SBVF. Rock hammer for scale in each picture (except A, using a 3 mm pencil tip). NAD27 GPS coordinates in two of the photos. A. hornblende xenocryst in Hog Pen Formation; metal object at top of photo is a 3 mm pencil tip. B. Flow breccia in the Hog Pen Formation. C. Xenolith (arrow) in the "turkey-track" lava in the upper Rattlesnake Member of the Three Rivers Formation. D. Spotted texture on weathered surface of the Taylor Windmill Member of the Three Rivers Formation. E. top of volcaniclastic conglomerate (Tvs) baked by the younger tuff of upper Nogal Canyon F. Welded Buck Pasture Tuff. Note the flattened and deformed brown clot to right and just above the rock hammer handle (white arrow). G. Flattened fiamme in welded Palisades Tuff. H. gradational contact between a block-and-ash flow breccia and a flow in the Rose Peak Trachyte. The base of the flow is toward the left.

zones of block-and-ash breccia, (5) an upper aphyric, vesicular trachyte-trachyandesite, and (6) a volcaniclastic interval. Here we elevate the Godfrey Hills "Trachyte" to group status (Godfrey Hills Group) and divide the group into two formations: the Lopez Spring Formation and the Husk Windmill Formation. The Husk Windmill Formation is further subdivided into five distinctive members (oldest to youngest): unnamed trachyte, the Palisades Tuff, Rose Peak Trachyte, Crawford Canyon Trachyte, and a volcaniclastic member.

Hog Pen Formation

The Hog Pen Formation comprises greenish-gray to purple-red debris flows and crystal-rich (15–20%), pyroxene-phyric basaltic trachyandesite to basalt flow breccias and lava flows (Figs. 2, 3). The angular to subrounded clasts, which resemble the lavas, in the debris flows have conspicuous pyroxene phenocrysts up to 3 cm long and hornblende and pyroxene xenocrysts up to 5 cm long (Fig. 5A, B). Pyroxene phenocrysts are generally 3–4 mm in diameter. Plagioclase generally makes up <50% of the discernible phenocrysts. Lava flows with megacrysts of hornblende and pyroxene near the base and a pyroxene-bearing flow in the middle of the Hog Pen Formation yield $^{40}Ar/^{39}Ar$ dates of 37.01 ±0.10 and 36.57 ±0.21 Ma, respectively (Table 1, samples 19 and 20).

Barber Ridge is composed exclusively of debris flows and pyroxene-phyric basaltic trachyandesite to trachybasalt flow breccia and lava flows of the Hog Pen Formation. Debris flows high in the section have a pronounced southerly dip. A distinctive lava flow with abundant hornblende xenocrysts up to 5 cm across is exposed on the west end of the ridge about 30 m above the contact with the underlying Eocene Sanders Canyon Formation (Fig. 5A). This flow is likely equivalent to unit 2 on the Thompson (1964, 1973) section (Fig. 2). The red fine-grained sandstone of the Sanders Canyon Formation appears to be intercalated with the basal 30 m of the pyroxene-phyric unit on the south-central part of Barber Ridge. The basal contact of the pyroxene-phyric unit is more abrupt on the north side of the ridge.

Three Rivers Formation

The Hog Pen Formation is gradationally overlain by the ***Rattlesnake Canyon Member*** of the Three Rivers Formation. This succession is made up of crystal-rich (10–30%) porphyritic basaltic trachyandesite flows with 3–4 mm plagioclase laths as the dominant phenocryst, with lesser amounts of pyroxene (Figs. 2, 3). The lava is intercalated with subordinate volumes of volcaniclastic sediment, pyroxene-phyric porphyritic basaltic trachyandesite, and crystal-poor trachybasalt (Fig. 3). One to two flows of distinctive "turkey track" lava with 15–25% plagioclase laths that are 2–3 cm long characterize the upper part of the Rattlesnake Canyon Member; these flow commonly contain xenoliths of older porphyritic lavas (Fig. 5C). We mapped these turkey-track lavas from the south side of Three Rivers Canyon north to Water Canyon, where the lava flows pinch out. These unique lava flows are 6–10 m thick on the western escarpment of Sierra Blanca and are only 1 m thick in the western Godfrey Hills.

The overlying ***Taylor Windmill Member*** is a more mafic unit with thin flows of aphanitic to crystal-poor (<1–2% plagioclase and pyroxene phenocrysts) trachybasalt and basaltic trachyandesite intercalated with thick beds of red, deeply weathered, volcaniclastic pebbles to cobbles. These lavas commonly have a silky or spotted appearance on a weathered surface (Fig. 5D). A trachybasalt in this unit has an imprecise $^{40}Ar/^{39}Ar$ date of 37.84 ±0.48 Ma (Table 1, sample 18) that does not fit the observed stratigraphic relations. The top of the Taylor Windmill Member near the crest of the Sierra Blanca massif contains a thick, extensive flow, the Spring Canyon trachyte (36.87 ±0.13 Ma; Table 1, sample 17) that is petrologically and chemically distinct from underlying strata (Thompson, 1973; Goff et al., 2011a).

The ***Argentina Spring Tuff Member*** ($^{40}Ar/^{39}Ar$ date of 36.06 ±0.70 Ma; Table 1, sample 16) on the Sierra Blanca massif is a lithic-rich, rheomorphic tuff of rhyolitic composition that overlies the Spring Canyon trachyte and the Taylor Windmill Member in the northern part of the Sierra Blanca block; this tuff pinches out to the south. This important marker unit commonly has a laminar to swirling fluidal fabric on weathered surfaces. Phenocrysts (5–15%) include sanidine, biotite, and plagioclase (Goff et al., 2011a). Trachybasaltic and basaltic trachyandesitic crystal-poor lavas that are present up-section above the southern margin of the Argentina Spring Tuff on the Sierra Blanca massif are included in the Taylor Windmill Member (Fig. 4).

Purplish gray to red volcaniclastic sandy conglomerates containing discontinuous plagioclase- and amphibole-phyric lava flows above the Argentina Spring Tuff Member are assigned to the ***Double Diamond Member***. Pyroxene and potassium feldspar phenocrysts are also present in variable proportions in these lavas. Among the Double Diamond Member lavas is the Spring Point trachyandesite ($^{40}Ar/^{39}Ar$ date of 35.32 ±0.16 Ma; Table 1, sample 15), which forms a prominent plug and associated flow above the Argentina Spring Tuff.

A second rheomorphic tuff deposit (***tuff of upper Nogal Canyon***) that contains at least one interbedded volcaniclastic sediment interval that is baked by the upper tuff deposit is exposed on the north and west sides of Nogal Peak above the amphibole-bearing lavas of the Double Diamond Member of the Three Rivers Formation (Fig. 5E). This tuff is highly variable in thickness (10–60 m). The tuff of upper Nogal Canyon was included in the Nogal Peak Trachyte by Thompson (1973), but this tuff interval is considered to be a separate mappable unit here (Fig. 2). The exact relationship of the tuff of upper Nogal Canyon at the base of Nogal Peak to the underlying Double Diamond Member on the Sierra Blanca block is not clear because of poor exposures. This tuff succession is interpreted to be interbedded with the Double Diamond Member.

Nogal Peak Trachyte

The Nogal Peak Trachyte is a biotite-bearing, fine-grained gray lava. A biotite $^{40}Ar/^{39}Ar$ date of 31.41 ±0.38 Ma (Table 1, sample 10) was determined from a trachyte flow that overlies the tuff of upper Nogal Canyon on a ridge north of Nogal Peak in the headwaters of Norman Canyon. Recent mapping revealed a vent of alkali basalt (alkali basalt of Hill 9500) that cuts the Nogal Peak Trachyte southwest of Nogal Peak (Goff et al., 2011a); thus the Hill 9500 lava, which has small pyroxene and plagioclase phenocrysts, is the youngest lava preserved near Nogal Peak. The Hill 9500 lava is cut by a biotite syentite dike that is likely related to the nearby 31–32 Ma Rialto stock.

Church Mountain Phonolite

The Church Mountain lavas contain potassium feldspar, plagioclase, and biotite phenocrysts. Recent geochemical and geochronologic analyses (Table 1) of the Church Mountain succession above the Walker Group at the north end of the Sierra Blanca massif (Cikoski et al., 2011) indicate that these lavas are phonolites erupted at 32.95 ±0.12 to 32.71 ±0.13 Ma (Table 1, samples 12 to 13). Thus, the Church Mountain Latite is renamed the Church Mountain Phonolite and includes lavas and minor volcaniclastic sedimentary rocks. Two distinctive crystal-rich lava flows with abundant phenocrysts of potassium feldspar, plagioclase feldspar, and pyroxene, Kountz Canyon and Gaylord Peak flows, are mappable flows within the Church Mountain area. The two lavas flowed northward, filling rugged paleovalleys that cut down into the Walker Group (Figs. 1, 4; Cikoski et al., 2011).

Godfrey Hills Group

Several of the units exposed on Sierra Blanca and Barber Ridge are also exposed in the Godfrey Hills (Figs. 1, 3). Thinned intervals of the Hog Pen Formation and the Rattlesnake Canyon Member of the Three Rivers Formation are exposed above the Eocene Sanders Canyon Formation in the northwestern and central Godfrey Hills. The Taylor Windmill Member is thick in the northern Godfrey Hills, but the Argentina Spring Tuff Member and the reddish volcaniclastic Double Diamond Member are absent.

The lithic and clot-bearing Buck Pasture Tuff, which fills east-striking paleovalleys, sits above the Taylor Windmill Member in the Godfrey Hills. Phenocrysts include sanidine, plagioclase, biotite, and pyroxene. The Buck Pasture Tuff (34.28 ±0.05 Ma; Table 1, sample 14) consists of two flow units separated by an interval of volcaniclastic sediment at several localities in the northern Godfrey Hills, and this tuff superficially resembles the tuff of upper Nogal Canyon; however, a source for the Buck Pasture Tuff might be located within the Godfrey Hills. A spectacular exposure of this unit is located northwest of Rose Peak (square labeled BPT on Fig. 1), preserving ~60 m of strongly welded (Fig. 5F) and moderately welded intervals. The tuff at the base and near the center of this exposure is only moderately welded, containing approximately 5–7% brown porphyritic clots that are variably flattened or equant and 7–10% lithic fragments. This unit grades up into a more welded zone. Moving upward, the middle part of this exposure is moderately welded and is dominated by brown porphyritic clots (25–35%) that are equant and have prominent reaction rims. The top part of the exposure has another zone of moderately welded tuff grading upward into strongly welded, with pronounced flattening of the brown clots. Pumice is rare (<5%) in this tuff. The volume of clots in the Buck Pasture Tuff and the thickness of the tuff decreases north and south of this exposure, suggesting this outcrop could be near the source. The abundance of lithic fragments might also indicate proximity to the vent. A volcaniclastic interval is preserved in this outcrop.

The section immediately above the Buck Pasture Tuff Member of the Three Rivers Formation is characterized by several spatially and lithologically distinctive lavas and volcaniclastic sediments. The proposed Godfrey Hills Group includes both the Lopez Spring and the Husk Windmill Formations. At the south end of the Godfrey Hills, the lower part of the ***Lopez Spring Formation*** includes a thick (up to 85 m), irregularly eroded, aphyric trachyandesite with a poorly constrained $^{40}Ar/^{39}Ar$ age of 31.05 ±0.76 Ma (Table 1, sample 11) that filled a northeast-striking paleovalley. This unit is absent in the northern Godfrey Hills. Volcaniclastic sediments with trachyte clasts containing abundant biotite are discontinuously exposed in both the southern and the northern Godfrey Hills (Fig. 4). A trachyte cobble from debris flows in the middle part of the volcaniclastic interval yielded a biotite $^{40}Ar/^{39}Ar$ date of 30.04 ±0.2 Ma (Table 1, sample 9), providing a maximum age for the sediment. Along the southern end of the hills, dark brown, discontinuous trachyandesite lava flows are common near the top of the section. Crystal-rich lava flows with potassium feldspar that resemble the Kountz Canyon flow and a flow with an equigranular matrix occupy this interval west of Rose Peak in the northern Godfrey Hills. We assign this lithologically diverse unit to the Lopez Spring Formation. The Lopez Springs Formation is 200 to 260 m thick.

The Lopez Spring Formation, which is predominantly volcaniclastic, is overlain by a succession of lava flows, tuffs, and volcaniclastic sediments herein assigned to the Husk Windmill Formation. This formation consists of several distinctive members. The lowest three units are sanidine-bearing trachyte to trachyte tuff. The oldest unit in the ***Husk Windmill Formation*** is a discontinuously exposed trachyte flow and flow breccia that is found only in the northern Godfrey Hills. This unnamed 28.78 ±0.04 Ma (Table 1, sample 8) trachyte has ~10% phenocrysts of plagioclase, biotite, and pyroxene. This cliff-forming unit is 60–70 m thick. The unnamed trachyte is overlain by the 28.67 ±0.07 Ma (Table 1, samples 6 and 7) ***Palisades Tuff***, which is trachytic in composition and is found throughout the Godfrey Hills. The bold cliffs of Palisades Tuff are 25 to 90 m high. The welded tuff generally thickens to the north, but thins over the older trachyte highs. The tuff is lithic-poor, with < 2% lithic fragments composed of trachyandesite and trachyte lavas, and is characterized by strongly flattened fiamme (Fig. 5G). Phenocrysts include plagioclase, sanidine, pyroxene, magnetite, and sparse biotite and hornblende. The tuff is generally crystal-poor (~5–10% phenocrysts), but the more welded intervals are 15–20% phenocrysts. Occasionally, the tuff has flattened brown porphyritic clots near the base.

The tuff is overlain by a sparsely porphyritic trachyte, the ***Rose Peak Trachyte***, (28.59 ±0.05 Ma, Table 1, sample 3) that contains discontinuous zones of breccia (Fig. 5H). The base of this unit contains biotite at the north end of the Godfrey Hills. Phenocrysts

(<7–10%) of sanidine and pyroxene, plagioclase, magnetite, and sparse hornblende characterize this lava. Red fine-grained sandstone commonly occurs below the basal breccia of the unit and above the Palisades Tuff. The Rose Peak Trachyte appears to have filled a paleovalley cut into and through the Palisades Tuff at the northern tip of the Godfrey Hills. Dikes of this composition and age ($^{40}Ar/^{39}Ar$ date of 28.53±0.03 Ma; Table 1, sample 4) are located on the west side of Rose Peak. These dikes suggest the trachyte was emplaced via fissure-type eruptions. The Rose Peak Trachyte is 100 to 120 m thick.

The Rose Peak Trachyte is overlain by multiple thin, vesicular flows of aphanitic trachyte to trachyandesite, herein named the ***Crawford Canyon Trachyte***. A thin ashy biotite trachyte flow and tuff, which returned a $^{40}Ar/^{39}Ar$ biotite date of 28.60 ±0.05 Ma (Table 1, sample 2), are locally preserved in the middle of this unit south of Husk Windmill. This light to dark gray fine-grained lava has a trachytic texture and contorted platy flow foliation. Microphenocrysts are aligned plagioclase, pyroxene, and magnetite. The flows are 1 to 10 m thick with a basal scoriaceous breccia and vesicular flow tops with elongated vesicles. Red to yellow alteration of the flow breaks is common. The Crawford Canyon Trachyte is 300 to 370 m thick.

A 35 to 45-m thick volcaniclastic unit and a 5 to 15-m thick landslide deposit with blocks of Palisades Tuff and Rose Peak Trachyte cap the succession. A locally preserved vitric, lithic tuff with a $^{40}Ar/^{39}Ar$ date of 28.23 ±0.06 Ma (Table 1, sample 1) is located in the upper part of the volcaniclastic section.

A sanidine-bearing dike cutting the Crawford Canyon Trachyte Member of the Godfrey Peak Group south of Rose Peak and south of the northwest-striking Jackass Mountain fault (Koning et al., this volume) has a $^{40}Ar/^{39}Ar$ date of 28.57 ±0.18 Ma (Table 1, sample 19). This dike could conceivably have been the source of the local tuff in the Crawford Canyon Trachyte. Another dike on the east flank of Rose Peak yielded a complicated suite of sanidine $^{40}Ar/^{39}Ar$ dates with grain ages ranging from 17.9 to 29.3 Ma (Table 1, sample 20). The dike intrudes the Palisades Tuff; thus, many of the older grains are likely xenocrysts derived from the tuff. The significance of the younger ages is equivocal.

A trachyandesite sill (Fig. 3) with phenocrysts of hornblende, potassium feldspar, and pyroxene phenocrysts set in a fine-grained equigranular matrix is located just south of the Godfrey Hills, intruding both the Eocene Sanders Canyon Formation and the Hog Pen Formation. This sill has an unusually young $^{40}Ar/^{39}Ar$ groundmass date of 27.05±0.81 Ma. At this point, ~27 Ma appears to be the time of youngest magmatism in the SBVF.

DISCUSSION

Temporal and spatial eruption patterns

The available geochonological data reveal two relatively short-lived pulses of voluminous volcanism in the Sierra Blanca region. A third episode is confined to the north end of the range in the vicinity of Church Mountain. The Walker Group was erupted between about 38 – 34 Ma. The great thickness of the Hog Pen Formation in the northern part of the Sierra Blanca massif and on Barber Ridge and the presence of large volumes of debris flows within this unit (Kelley et al, 2011; Goff et al., 2011a) suggests that these lavas originated from now-eroded, steep sided stratovolcanoes in the northern part of the field. These flows thin northward between Barber Ridge and Hog Pen Canyon, indicating the loci of activity was likely east of Barber Ridge (Appendix 3). The “turkey-track” flows in the upper Rattlesnake Canyon Member of the Three Rivers Formation are thickest 3 km southeast of Ski Apache on Sierra Blanca (500–550 m, based on mapping by Moore et al., 1988a) and thin northward (Koning et al., this volume). Based on this thickness trend, we interpret that the main source of the “turkey track” lavas was near Ski Apache. The Taylor Windmill Member is thickest in the central part of the field, particularly in Bonito Canyon and near Nogal in proximity to a possible buried volcanic center. The red color and the deeply weathered nature of the clasts within the volcaniclastic intervals in the unit may hold clues to the warm, humid climate of late Eocene time (e.g., Koch et al., 1992). A change in the nature of the landscape of the northwestern SBVF is associated with cessation of Taylor Windmill eruptions. Prior to this time, Rattlesnake Canyon and Taylor Windmill lava flows traveled long distances over a subdued topography and overtopped low-amplitude interfluves, but after this time the flows were restricted to local paleovalleys. Thickness and preservation trends in the Argentina Spring Tuff and in the Double Diamond Member of the Three Rivers Formation point toward sources to the north, but a gentle northward tilt of the central Sierra Blanca massif may have enhanced preservation of strata in that direction. Dikes radiating from Double Diamond Peak, and hydrothermal alteration on the east side of the peak indicate a center in this area (Cikoski et al., 2011). Vents at Spring Point and near Argentina Peak (Goff et al., 2011a) also contributed lavas to the Double Diamond Member. The Buck Pasture Tuff is thickest northwest of Rose Peak; trends in the distribution of the porphyritic brown clot and lithics suggest proximity to a source here. The variable thickness of Buck Pasture Tuff/ tuff of upper Nogal Canyon and the presence of volcaniclastic interval within the unit in places indicates erosion occurred prior to and during eruption at ~34 Ma. The source of the tuff of upper Nogal Canyon remains enigmatic.

Erosion again prevailed prior to significant eruptions in the Church Mountain area at 32.7 Ma. Erosion followed by minor volcanism at 31 Ma occurred in the Godfrey Hills and Nogal Peak areas. Small volume eruptions and low sedimentation rates continued until about 28.8 Ma, when the Husk Windmill Formation was primarily deposited within a time interval of only ca. 0.6 Ma. As pointed out by Goff et al. (2011b), the timing of the emplacement of the three phases of the Three Rivers Stock (27 ±2 to 28.9 ±0.18 Ma; $^{40}Ar/^{39}Ar$ dates) spans this time interval and the quartz syenites are chemically similar to the Palisades Tuff in both major and trace elements. Thus, the source of the sanidine-bearing Palisades Tuff in the Husk Windmill Formation is likely the Three Rivers stock (Goff et al., 2011a, 2011b). Sources of the trachytic lavas and tuffs above and immediately below the Palisades Tuff (Fig. 4) are not clear. Thin tuffs in the upper part of the Husk Windmill Formation may be from localized eruptions associated with NE-striking sanidine-bearing dikes, as discussed above. In summary, volcanic activity in the northwestern SBVF waned at ca. 28 Ma and the youngest intrusive activity (sill at ca. 27 Ma) coincides with the youngest Three Rivers intrusions.

Geochemical trends

Our limited geochemical data set reveals a weak correlation of rock chemistry with age (Fig. 2). Generally the older rocks are more mafic, trending toward more felsic and alkalic rocks through time, as noticed by previous workers in the SBVF. One notable exception to this trend is the Hill 9500 basalt flow that rests on the Nogal Peak Trachyte. The volume of tuff erupted from the SBVF is small compared to other fields like the Mogollon-Datil and San Juan that formed during the late Eocene to early Oligocene ignimbrite flare-up (Davis and Hawkesworth, 1993; Colucci et al, 1991). Only one caldera and trace volumes of rhyolite (<1% of the total volume) have been identified in the SBVF (Goff et al., this volume). The trachytic composition and small volume of the tuffs (<5% of the total volume) suggest that the magma chambers below the SBVF did not contain a significant felsic crustal component. Geographic position within the volcanic field also affected the composition of the volcanic rocks, with rocks at the north end showing increased alkali content compared to those to the south, suggesting a variability in the chemistry of the underlying upper mantle that has been observed in other volcanic fields (e.g., Jemez Mountains volcanic field, Wolff et al., 2005; Rowe et al., 2007). The preliminary data, observations, stratigraphic framework and ages presented here set the stage for more detailed geochemical studies in the future.

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