# *Geochemistry and geochronology of intrusive and volcanic rocks of the Three Rivers stock, Sierra Blanca, New Mexico*

Fraser Goff, Robert C. Roback, William McIntosh, Cathy J. Goff, and Emily C. Kluk

2014, pp. 183-196. https://doi.org/10.56577/FFC-65.183

*in:*

*Geology of the Sacramento Mountains Region*, Rawling, Geoffrey; McLemore, Virginia T.; Timmons, Stacy; Dunbar, Nelia; [eds.], New Mexico Geological Society 65 th Annual Fall Field Conference Guidebook, 318 p.
https://doi.org/10.56577/FFC-65

*This page is intentionally left blank to maintain order of facing pages.*

# GEOCHEMISTRY AND GEOCHRONOLOGY OF INTRUSIVE AND VOLCANIC ROCKS OF THE THREE RIVERS STOCK, SIERRA BLANCA, NEW MEXICO

FRASER GOFF[1], ROBERT C. ROBACK[2], WILLIAM McINTOSH[1, 3], CATHY J. GOFF[4], AND EMILY C. KLUK[2]
[1] Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM, candf@swcp.com
[2] Earth and Environmental Sciences Division, Group EES-14, Los Alamos National Laboratory, NM
[3] New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM
[4] Consultant, Los Alamos, NM

**ABSTRACT**—Recent geologic mapping of the Three Rivers stock has outlined four relatively large syenite to quartz syenite bodies with distinct textural characteristics emplaced at roughly 29 to 28 Ma. These syenitic rocks were later intruded by a variety of smaller volume alkali granites (27.7 to 27 Ma). Three small rhyolites, which have geochemical affinities to the alkali granites, were identified around the north margin of the stock. The age of the freshest of these rhyolites is 28.2 Ma. A last group of two dikes and a small plug (rhyolite, trachyte and monzonite, respectively) conclude the intrusive activity in the stock, but these units are significantly younger (25.9 to 25.4 Ma), geochemically different, and volumetrically insignificant when compared to the main stock. The west margin of the stock has been unroofed and deeply eroded by uplift along normal faults that separate the west margin of Sierra Blanca from the Tularosa Basin. Two geochemical traverses down the highly eroded scarp of the syenite body show that the syenite is more silicic (evolved) at the top of the intrusion than at the bottom and core. The combined data suggest that the syenite is the crystallized remnant of a zoned magma chamber and that the Three Rivers stock represents an upper level intrusive complex beneath a small, eroded caldera.

## INTRODUCTION

The Sierra Blanca (White Mountains) lie in south-central New Mexico between the towns of Carrizozo on the northwest, Ruidoso on the southeast, and Bent on the south (Fig. 1). The landscape consists of a deeply dissected, north-trending horst of mostly mid-Tertiary volcanic rocks and associated volcaniclastic rocks (Sierra Blanca Volcanics; Thompson, 1973) intruded by three somewhat younger dioritic to syenitic stocks (Bonito Lake, Rialto and Three Rivers stocks). These stocks form part of the intrusive complex that makes up the Lincoln County porphyry belt, a significant mining region in New Mexico (Allen and Foord, 1991; Woodward, 1991, McLemore et al., this volume). Just west of the Sierra Blanca, a number of prominent normal faults offset the stock and enclosing volcanic rocks from the Tularosa Basin. Sierra Blanca Peak crests at 3660 m (Fig. 2) whereas the Tularosa Basin lies at elevations of roughly 1200 to 1850 m, making this pair of features one of the largest and most spectacular tectonic offsets in the United States (Fig. 3). The White Mountains Wilderness occupies the core of the Sierra Blanca; thus much of the range is accessible only by foot or horseback. The Mescalero Apache Reservation owns the south end of the range and operates the well-known Ski Apache. During 2009 to 2011, the geology of the Three Rivers stock and adjacent mountains was mapped at a scale of 1:24,000 (Goff et al., 2011a) and this map, along with bordering quadrangle maps, has been compiled into a regional geologic map of the western Sierra Blanca Basin (Koning et al., 2014). In this paper, we present whole-rock geochemical data and $^{40}Ar/^{39}Ar$ ages of intrusive and volcanic rocks of the Three Rivers stock to demonstrate that the intrusive complex is the root of an uplifted and eroded caldera.

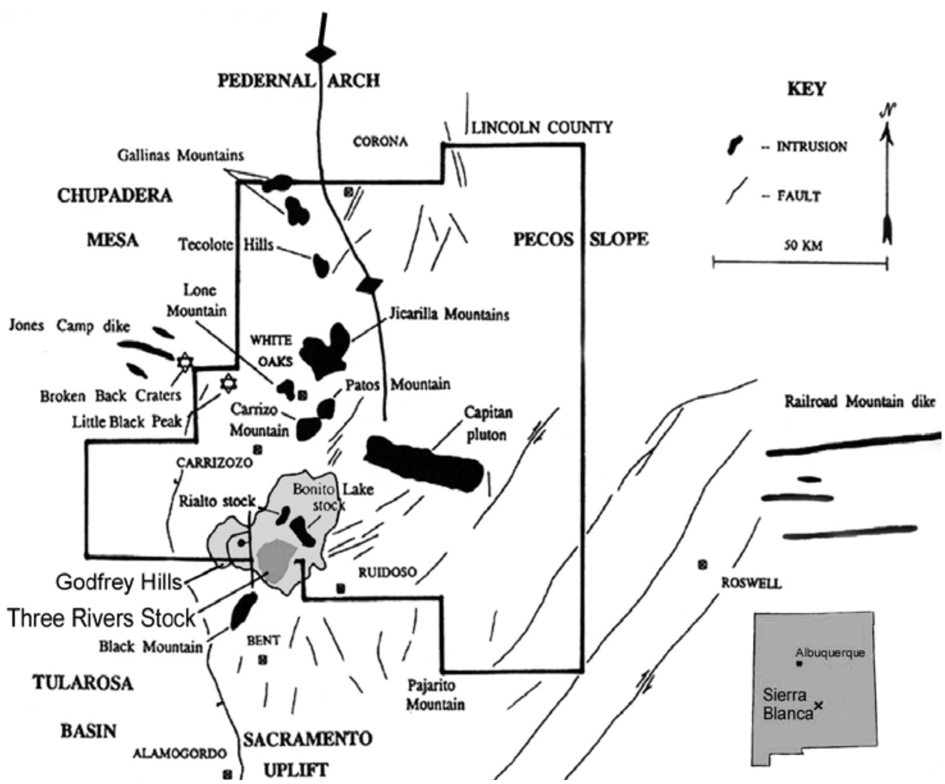


FIGURE 1. Map of the Lincoln County porphyry belt, New Mexico shows most of the named mid-Tertiary intrusive bodies. Sierra Blanca volcanics (ca. 38 to 32 Ma) are shown in pale gray enclosing the Three Rivers stock (ca. 29 to 25 Ma) in medium gray. Stars indicate vents for the Quaternary Carrizozo basalt flows (modified from Allen and Foord, 1991).

## GEOLOGY OF THREE RIVERS STOCK

The first comprehensive descriptions of the geology, stratigraphy, structure and economic potential of the Sierra Blanca and Three Rivers stock were published by Thompson (1966, 1972, 1973). Three Rivers stock (Figs. 1 and 2) is considerably larger and more complex than the other two stocks in the Sierra Blanca (Bonito Lake and Rialto), covering an area of roughly 75 km$^2$. It is also compositionally more evolved, consisting of distinct masses of syenite to alkali granite with many crosscutting dikes and small plugs of intermediate to silicic composition. Thompson (1973) stated the stock is "principally leuco-syenite porphyry." Giles and Thompson (1972) described three subunits, whereas Moore et al. (1988) working solely

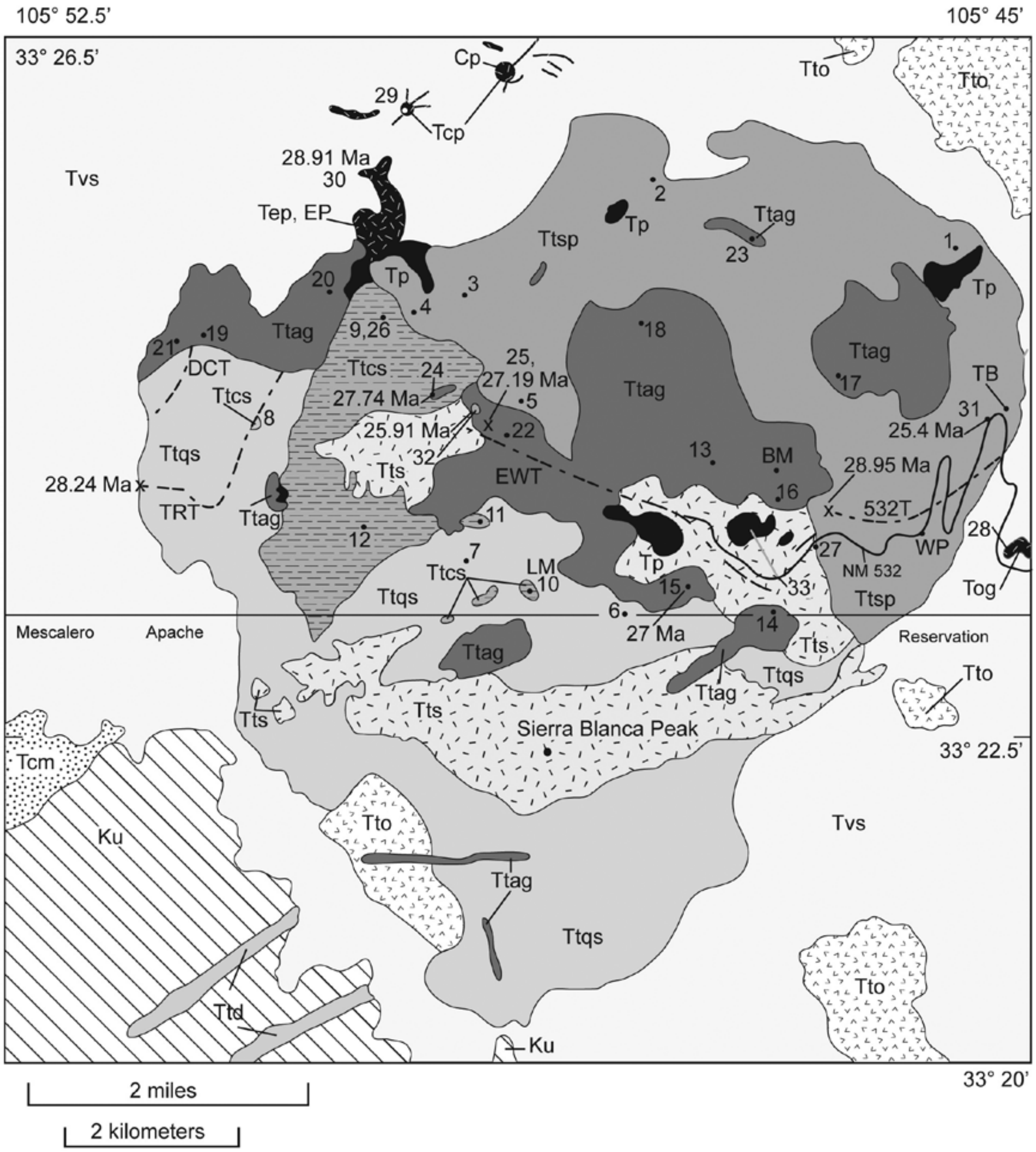


FIGURE 2. Simplified geologic map of the Three Rivers stock and surrounding area showing locations of samples described in Tables 1 and 2 (adapted from Moore et al., 1988 and Goff et al., 2011a). Sample traverses (see Table 2 and text): DCT = Dry Canyon Trail traverse, TRT = Three Rivers Trail traverse, EWT = Southeast northwest traverse across unit Tts, 532T = traverse down east flank of unit Ttsp across NM 532. Numbers 1 to 33 show locations of isolated samples listed in Table 2. Map symbols: Ttsp = quartz syenite porphyry (nordmarkite - gray), Ttqs = quartz syenite to alkali granite (light gray), Tts = coarse-grained syenite (black hatcher on white background), Ttcs = very coarse-grained syenite (horizontal dash), Ttag = alkali granite, all types (dark gray), Tp = roof pendants and stoped blocks (black), Tcp, Tep, and Tog = Three Rivers rhyolites (white hatcher on black background), unlabeled lines and small gray dot = younger intrusions Ttbrd, Ttbhd, and Tthbm, Tto = other intrusive bodies of various ages (random black v pattern), Tvs = Sierra Blanca volcanic and subordinate volcaniclastic rocks (off white), Ttd = Black Mountain mafic dike swarm (pale gray), Tcm = Cub Mountain Formation (random black dots), Ku = Cretaceous rocks, undivided (diagonal black lines). Place names: BM = Buck Mountain, CP = Cone Peak, EP = Elk Point, LM = Lookout Mountain, TB = Texas Bend on NM 532, WP = Windy Point. (See also Color Plate 10)

on Mescalero Apache lands described five units. However, one of those five units (sodalite-nepheline syenite) occurs as a small plug south of the main mass of the stock. Goff et al. (2011a) mapped five major subunits including substantial volumes of alkali granite. Contacts between subunits are relatively sharp (often less than 1 m between distinct rock types) to gradational, and most contacts are relatively high-angle (dips greater than 70°) to vertical. In addition, separate bodies of syenite and alkali granite have varying textures (fine-grained, coarse-grained, porphyritic, etc.) and compositions such that some of the subunits and their boundaries are subjective, both in terms of mapping and chemistry. Crosscutting relations among units indicate the alkali granites post-date most of the syenitic rocks. Many of the syenites contain "mafic" xenoliths or enclaves of fine-grained igneous rocks described in detail below (see Fig. 4 to view textural variations of units). Igneous petrologists interpret the enclaves as injections of hotter intermediate to mafic magma that chilled as ellipsoidal masses within a pre-existing silicic host (Wilson, 1989, p. 80; Didier and Barbarin, 1991; Stimac and Pearce, 1992; Goff et al., 2014, p. 96).

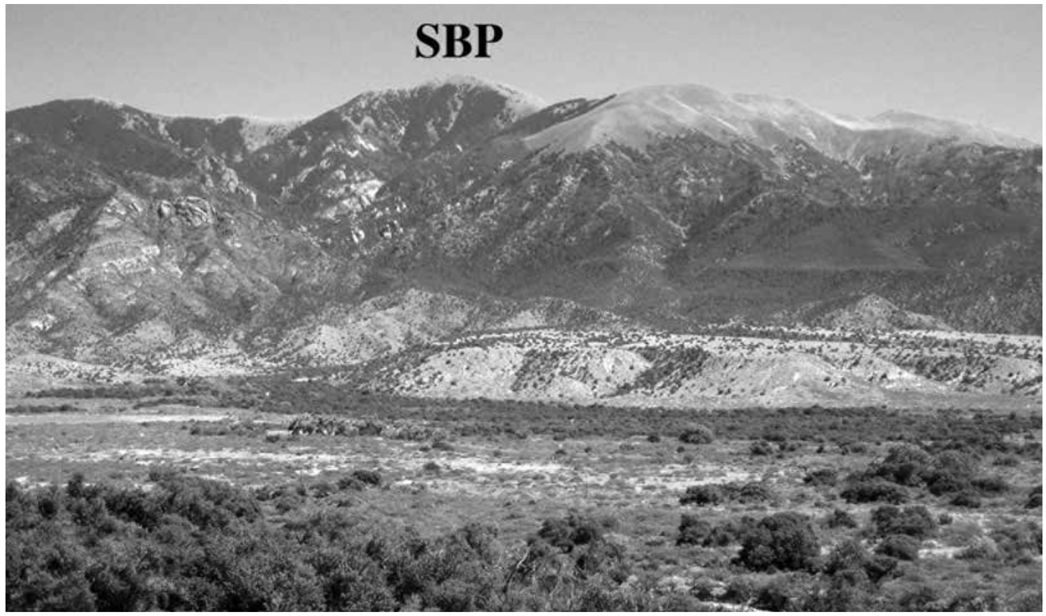


FIGURE 3. View east of Sierra Blanca from southern tip of Godfrey Hills near Santo Niño de Atocha Church (elevation about 1650 m). Sierra Blanca Peak (SBP) crests at 3660 m. The escarpment separates the Sierra Blanca from the Tularosa Basin. *(Photo by F. Goff)*

Giles and Thompson (1972) describe one of the major Three Rivers units as "nordmarkite" (quartz syenite porphyry, Williams et al., 1954), which has a brownish to purplish gray fine groundmass and conspicuous pink anorthoclase phenocrysts. The nordmarkite (unit Ttsp) differs from other syenites in the stock, which are generally white to gray and coarser-grained. Along NM Highway 532, the contact between nordmarkite and contrasting white coarse-grained quartz syenite (unit Tts) is quite sharp (Moore et al., 1988) providing a good basis for distinguishing this unit from other syenites. Elsewhere, the field distinction between nordmarkite and generic syenite porphyry as shown on the map by Giles and Thompson (1972) is difficult to apply; thus, the maps of Giles and Thompson (1972) and Goff et al. (2011a) differ in detail.

The Three Rivers stock intrudes a variety of older volcanic rocks comprising the Sierra Blanca Volcanics (Moore et al., 1988; Goff et al., 2011a). These consist of tephrite, basanite, alkali basalt, trachybasalt, trachyandesite and minor trachydacite ranging in age from about 37 to 34 Ma (Koning et al., 2014). At least three rhyolite bodies flank the edge of the stock (Elk Point rhyolite, Cone Peak rhyolite and Oak Grove rhyolite sill), and are chemically similar to the alkali granites in the stock (described below); thus, we believe they are genetically related to the Three Rivers stock. Finally, several dikes of syenite to rhyolite composition cut the stock and one small plug of monzonite intrudes the core of the stock.

Giles and Thompson (1972) identified several stoped blocks of volcanic rocks within Three Rivers stock. During our mapping, we found many more of these blocks ranging from only a few meters to one 700 by 250 m block exposed in Ski Apache (Fig. 5). Many, but certainly not all, blocks occur along contacts between different intrusive phases or near the stock boundary. In all cases, these blocks are contact metamorphosed and silicified but their original volcanic textures remain. Several roof pendants of volcanics also occur on top of the stock. The most impressive is the continuous pendant capping the west margin of the stock in upper Three Rivers and Dry Creek canyons (Fig. 6), but two other large pendants occur south of Elk Point and the northeastern part of the stock. The latter two pendants are deformed and faulted along the stock margin. Vertical contacts of the stock with volcanic wall rock are difficult to find even though the contact is easy to map. One such location occurs in the bed of lower Dry Creek where quartz syenite cuts basalt lava (Fig. 4D). Although contact metamorphosed, the lava still retains its texture of intergrown plagioclase, augite and olivine.

Paterson et al. (1991) discuss pluton emplacement mechanisms at length. Many controversies remain on the subject. Giles and Thompson (1972) proposed a three-component, "concentric shell" model for emplacement of the stock, which we think is too simplistic. To us, the stock shows strong evidence for a) initial, non-concentric injections of several chemically similar syenite melts, b) concurrent stoping of country rocks during each injection, c) later intrusion of more centralized but chemically variable alkali granite melts, and d) final doming and faulting of the stock roof, which is observable along stock margins (Paterson et al., 1991, fig. 1).

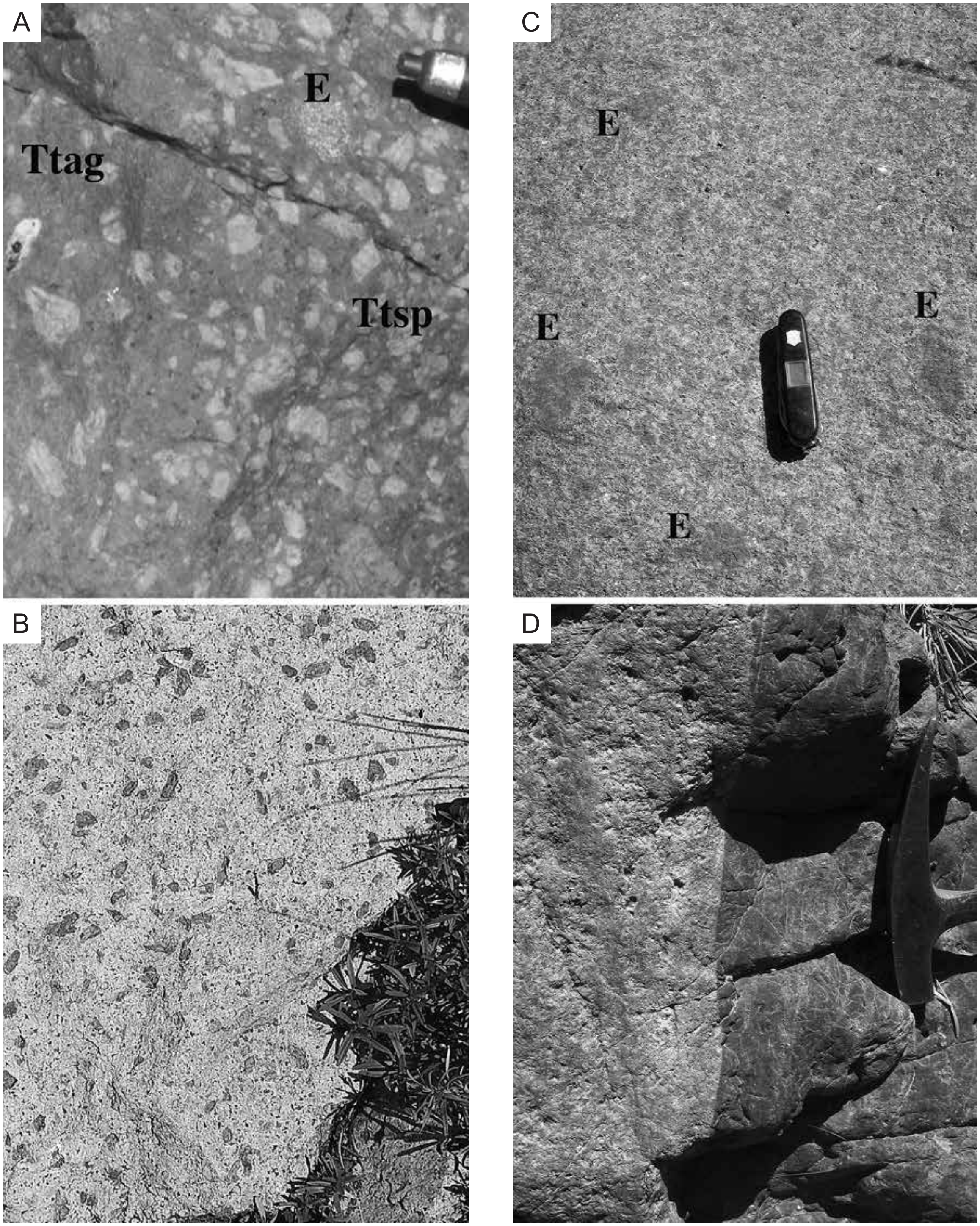


FIGURE 4. Textures and intrusive contacts displayed by some major units in the Three Rivers stock. A. Gradational boundary between quartz syenite porphyry (Ttsp, right) and alkali granite (Ttag, left) in the vicinity of sample site 17 (Fig. 2, tip of walking pole for scale). Phenocrysts of anorthoclase from the syenite are mingled into the boundary zone of the granite making the latter slightly porphyritic. Nonetheless, chemical analysis of rock from site 17 shows it to be one of the $K_2O$-rich alkali granites (Table 2). Note the small mafic enclave (E) in the syenite. B. Quartz syenite (Ttqs) showing blue-gray anorthoclase in medium-grained matrix, C. Very coarse-grained syenite (Ttcs) showing abundant mafic enclaves (E). D. Vertical intrusive contact between medium-grained quartz syenite (Ttqs, left) and contact metamorphosed olivine basalt of the Sierra Blanca Volcanics (right, Tvs) in the bottom of Dry Canyon (Fig. 2, head of rock hammer for scale). A thin section of the rock along this boundary shows that the basalt texture is preserved, although the rock matrix is metamorphosed. A chemical analysis of sample F13–64 from a few meters left of the contact (Table 2) shows it is the least evolved syenite in the Dry Canyon sample traverse (Fig. 6). *(Photos by F. Goff)* (See also Color Plate 9)

TABLE 1. $Ar^{40}/^{39}$ geochronology for intrusive and volcanic rocks of the Three Rivers stock, Sierra Blanca, New Mexico.[1]

| Sample no. | Location | Rock Type | Geology | Easting[2] | Northing | Phase | Age analysis[3] | Steps/ analysis | Age (Ma) ±2 sigma | MSWD[4] |
|---|---|---|---|---|---|---|---|---|---|---|
| **F09-107** | SE of Buck Mountain | Quartz syenite porphyry | Oldest intrusive body | 427582 | 3695319 | Kspar | LSH | 4 | 28.95 ±0.18 | 5.01 |
| **F09-118** | East margin of stock | Bio rhyolite dike | Cuts stock and border rxs | 429849 | 3695817 | Biotite | LSH | 5 | 25.4 ±0.8 | na |
| **F09-135** | Upper Ski Apache | Alkali granite | Intrudes syenite | 426305 | 3694614 | Na-amph | LSH | 9 | 27 ±2 | 5.6 |
| **F09-140c** | Three Rivers Canyon | Quartz syenite | Contact with border rxs | 420125 | 3695815 | Kspar | LSH | 3 | 28.24 ±0.19 | 0.55 |
| **F10-71** | Elk Point | Porph alkali rhyolite | NW margin of stock | 422713 | 3699411 | Sanidine | LF | 13 | 28.19 ±0.15 | 1.68 |
| **F10-76** | Along Crest Trail | Alkali granite dike | Intrudes syenite | 423406 | 3696889 | Kspar | LSH | 12 | 27.74 ±0.10 | 12.09 |
| **F10-77** | Along Crest Trail | Bio-hbd monzonite plug | Intrudes syenite | 423713 | 3696588 | Biotite | LSH | 2 | 25.91 ±0.26 | na |
| **F10-78** | Near Crest Trail | Alkali granite plug | Intrudes syenite | 423813 | 3696364 | Biotite | LSH | 5 | 27.19 ±0.21 | 7.14 |

1. The ages of the first five samples are reported in Goff et al. (2011a)
2. UTM locations NAD27, zone 13.
3. LSH = laser step heating; LF = laser fusion
4. Mean Square Weighted Deviation

## METHODS

We hammered 1 to 2 kg samples of rock out of each outcrop for chemical analysis, $^{40}Ar/^{39}Ar$ dating, and thin section examination. Roughly 20 single polished thin sections were prepared from our sample suite on which we performed qualitative petrographic analyses (see Goff et al., 2011a, appendix 5).

Minerals from eight samples collected for dating (Table 1) were separated with standard heavy liquid, Franz magnetic separator and hand picking techniques. Samples were irradiated in a machined aluminum tray for seven hours at the U.S. Geological Survey, Denver, CO. Neutron flux monitor was Fish Canyon Tuff sanidine (FC-2) with an assigned age of 28.02 Ma. Analyses were performed on a Mass Analyzer Products 215–50 mass spectrometer on line with an automated all-metal extraction system. Flux monitors and samples were fused and/or step-heated by a 50 watt Synrad $CO_2$ laser.

Additionally, 54 specimens were prepared for chemical analysis (Table 2) by rough crushing 500 g of fragments from the original samples. During this process, we eliminated weathered or fractured pieces that looked non-representative. We analyzed 40 of the samples for major and trace elements at Los Alamos National Laboratory (LANL) using an automated Rigaku wavelength-dispersive X-ray fluorescence spectrometer. These samples were crushed and homogenized in 5–10 g portions in a tungsten-carbide ballmill. Sample splits were heated at 110 °C for four hours, and then allowed to equilibrate at ambient laboratory temperature for twelve hours. To obtain fusions disks, 1.25-g splits were mixed with 8.75 g of lithium metaborate-tetraborate flux and initially heated in a muffle furnace for 45 minutes at 1100 °C, followed by a second heating for 1 h at 1150 °C. Additional 1-g splits were heated at 1000 °C to obtain Loss on Ignition (LOI) measurements to be used in the data reduction program. Elemental concentrations were calculated by comparing X-ray intensities for the samples to those for 17 standards of known composition using "consensus values" from Govindaraju (1994). Intensities were reduced using the de Jongh model empirical method to calculate theoretical matrix correction coefficients (Rigaku Corporation, 2009). All Fe is reported as $Fe_2O_3$.

ALS Laboratory Group, Reno, Nevada and Vancouver, Canada analyzed the remaining samples for major and trace elements using their "complete characterization" package. For these analyses, all Fe is also reported as $Fe_2O_3$. Details of sample preparation and analysis can be found in ALS Laboratory Group (2011).

## PETROLOGIC VARIATIONS AND DATES OF ROCK TYPES

### Quartz Syenite Porphyry, Unit Ttsp

The northeast portion of Three Rivers stock consists primarily of quartz syenite porphyry (nordmarkite, unit Ttsp; Fig. 4A), probably the most distinctive and the oldest dated unit in the intrusive body. Most specimens have a brownish or purplish gray, fine-grained groundmass of alkali feldspar, minor quartz, very minor plagioclase, aegirine to aegirine-augite, sodic amphibole, biotite and ultrafine-grained hematite engulfing large pale pink anorthoclase phenocrysts (≤3 cm long) rimmed with microperthite (orthoclase) (Giles and Thompson, 1972). Opaque oxides, apatite, sphene and zircon are visible in thin sections, although quantities vary. The proportion of pink feldspar phenocrysts is highly variable, however, being more abundant along the top and interior of the stock than on the stock margins. Moore et al. (1991) state the amphibole in this unit is arfvedsonite, but preliminary electron microprobe analysis indicates it is a sodic amphibole with a composition between riebeckite and arfvedsonite. The nordmarkite contains mariolitic cavities ≤1 cm wide containing quartz and fluorite (see also Giles and Thompson, 1972, p. 2135). Very rare enclaves (xenoliths or "blobs;" see Didier and Barbarin, 1991, regarding terminology) of more mafic magma were injected and quenched in the nordmarkite host magma before it solidified (Fig. 4A; Stimac and Pearce, 1992; Goff et al., 2014). The enclaves generally show

TABLE 2. Major and selected trace element analyses of rock units in the Three Rivers stock, New Mexico. Values of major elements are in wt-% and normalized to 100%. Values of trace elements are in ppm. Trace elements Cr, Cu and Ni were analyzed but are not reported.

| Unit | Sample[1] | Fig. 2 location | Easting[2] | Northing | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nordmarkite, unit Ttsp, Hwy 532 area traverse, top to bottom** | **F09-107A** | 532T | 427993 | 3695541 | 65.7 | 0.95 | 16.01 | 4.01 | 0.16 | 0.71 | 0.83 | 6.04 | 5.37 | 0.25 |
| | **F13-78** | 532T | 428914 | 3695492 | 66.19 | 0.89 | 16.19 | 3.78 | 0.157 | 0.29 | 0.83 | 5.64 | 5.84 | 0.193 |
| | **F13-79** | 532T | 429016 | 3695640 | 66.47 | 1.00 | 16.14 | 4.17 | 0.166 | 0.08 | 0.43 | 4.11 | 7.21 | 0.229 |
| | **F13-80** | 532T | 429427 | 3695738 | 66.05 | 0.82 | 16.52 | 3.68 | 0.163 | 0.38 | 0.51 | 5.39 | 6.30 | 0.176 |
| | **F13-81** | 532T | 429774 | 3696301 | 66.49 | 0.94 | 16.33 | 4.19 | 0.182 | 0.03 | 0.36 | 4.26 | 7.00 | 0.209 |
| **Nordmarkite, unit Ttsp, other locations** | **F10-25** | 1 | 429395 | 3698461 | 64.84 | 0.94 | 16.29 | 3.95 | 0.196 | 0.77 | 1.01 | 4.73 | 7.04 | 0.235 |
| | **F10-63** | 2 | 426128 | 3699304 | 66.72 | 0.88 | 16.13 | 3.63 | 0.174 | 0.06 | 1.28 | 5.19 | 5.74 | 0.196 |
| | **F10-73** | 3 | 423693 | 3698091 | 64.21 | 1.02 | 17.59 | 4.10 | 0.145 | 0.51 | 1.12 | 5.88 | 5.10 | 0.330 |
| | **F10-75** | 4 | 423319 | 3697752 | 65.29 | 1.00 | 16.25 | 4.01 | 0.173 | 0.84 | 0.83 | 6.03 | 5.33 | 0.255 |
| | **F10-80** | 5 | 424308 | 3697302 | 65.79 | 1.00 | 16.43 | 4.10 | 0.172 | 0.33 | 0.52 | 5.85 | 5.55 | 0.259 |
| **Quartz Syenite, unit Ttqs, Dry Canyon Trail traverse, top to bottom** | **F13-58** | DCT | 421066 | 3697859 | 68.75 | 0.58 | 15.60 | 2.59 | 0.134 | 0.39 | 0.67 | 5.53 | 5.63 | 0.104 |
| | **F13-60** | DCT | 420834 | 3697468 | 71.72 | 0.56 | 14.08 | 2.71 | 0.039 | 0.36 | 0.18 | 4.64 | 5.66 | 0.053 |
| | **F13-61** | DCT | 420487 | 3697015 | 68.40 | 0.73 | 14.91 | 3.62 | 0.121 | 0.62 | 0.51 | 4.88 | 6.09 | 0.117 |
| | **F13-62** | DCT | 420431 | 3696872 | 67.79 | 0.67 | 15.62 | 3.23 | 0.112 | 0.51 | 0.60 | 5.25 | 6.09 | 0.117 |
| | **F13-64** | DCT | 420236 | 3696785 | 62.81 | 1.03 | 16.39 | 4.47 | 0.273 | 1.13 | 1.82 | 5.97 | 5.66 | 0.452 |
| **Quartz Syenite, unit Ttqs, Three Rivers Trail traverse, top to bottom** | **F11-40** | TRT | 421782 | 3697224 | 70.11 | 0.57 | 15.17 | 2.38 | 0.097 | 0.33 | 0.32 | 4.85 | 6.10 | 0.067 |
| | **F11-39** | TRT | 421683 | 3697178 | 69.46 | 0.57 | 15.36 | 2.38 | 0.113 | 0.36 | 0.62 | 5.07 | 6.01 | 0.066 |
| | **F13-65** | TRT | 420790 | 3696477 | 67.77 | 0.71 | 15.71 | 3.00 | 0.100 | 0.59 | 1.08 | 5.40 | 5.52 | 0.119 |
| | **F13-66** | TRT | 420604 | 3695785 | 63.16 | 1.02 | 17.39 | 4.34 | 0.136 | 1.04 | 2.18 | 5.80 | 4.68 | 0.268 |
| | **F13-67** | TRT | 420604 | 3695685 | 68.17 | 0.68 | 15.56 | 3.02 | 0.130 | 0.44 | 0.77 | 5.23 | 5.89 | 0.101 |
| | **F11-15A** | TRT | 420125 | 3695815 | 66.60 | 0.89 | 15.60 | 3.72 | 0.220 | 0.71 | 0.93 | 5.77 | 5.35 | 0.230 |
| **Quartz Syenite, unit Ttqs, other locations** | **F09-136A** | 6 | 425819 | 3694477 | 67.3 | 0.84 | 15.98 | 3.33 | 0.12 | 0.54 | 0.58 | 5.56 | 5.58 | 0.14 |
| | **NCP-18** | 7 | 423889 | 3695238 | 68.25 | 0.69 | 15.86 | 2.42 | 0.039 | 0.63 | 0.43 | 5.62 | 5.96 | 0.098 |
| **Coarse-grained Syenite, unit Tts, east to west traverse** | **F13-77** | EWT | 427815 | 3695325 | 65.69 | 0.99 | 16.30 | 4.04 | 0.168 | 0.59 | 0.57 | 5.56 | 5.88 | 0.217 |
| | **F09-102A** | EWT | 427397 | 3694661 | 66.00 | 1.05 | 16.30 | 4.03 | 0.170 | 0.61 | 0.55 | 5.44 | 5.55 | 0.260 |
| | **F13-83** | EWT | 427160 | 3695324 | 65.09 | 0.89 | 16.65 | 3.91 | 0.140 | 0.74 | 0.80 | 5.47 | 6.10 | 0.222 |
| | **F13-89** | EWT | 426622 | 3695650 | 64.05 | 1.14 | 16.60 | 4.76 | 0.171 | 0.73 | 1.09 | 6.12 | 5.06 | 0.278 |
| | **F13-86** | EWT | 423827 | 3696359 | 65.40 | 1.09 | 15.89 | 3.81 | 0.089 | 1.08 | 1.15 | 5.91 | 5.27 | 0.315 |
| **Very Coarse-Grained Syenite, unit Ttcs, various locations** | **F09-139A** | 8 | 421290 | 3696930 | 64.7 | 0.98 | 16.05 | 4.14 | 0.20 | 0.86 | 1.27 | 6.28 | 5.22 | 0.28 |
| | **F10-74** | 9 | 423222 | 3697580 | 64.55 | 0.96 | 16.55 | 4.02 | 0.157 | 0.78 | 1.21 | 6.11 | 5.38 | 0.276 |
| | **F10-86** | 10 | 424584 | 3694679 | 64.62 | 1.01 | 16.57 | 4.13 | 0.198 | 0.88 | 1.21 | 5.91 | 5.20 | 0.283 |
| | **F13-88** | 11 | 423977 | 3695534 | 62.50 | 1.28 | 15.94 | 6.56 | 0.086 | 1.27 | 1.30 | 5.80 | 4.87 | 0.399 |
| | **NCP-14** | 12 | 422508 | 3695650 | 64.43 | 1.08 | 15.99 | 4.54 | 0.182 | 0.98 | 1.21 | 6.08 | 5.21 | 0.302 |
| **Alkali Granite, unit Ttag, various locations** | **F09-105A** | 13 | 426225 | 3696160 | 71.3 | 0.75 | 15.10 | 1.21 | 0.01 | 0.04 | 0.22 | 0.86 | 10.34 | 0.13 |
| | **F09-109** | 14 | 427358 | 3694388 | 67.99 | 0.78 | 16.13 | 3.00 | 0.178 | 0.04 | 0.24 | 5.60 | 5.94 | 0.107 |
| | **F09-135A** | 15 | 426305 | 3694614 | 75.2 | 0.48 | 11.02 | 3.81 | 0.11 | 0.13 | 0.15 | 4.02 | 5.00 | 0.02 |
| | **F10-21** | 16 | 427447 | 3695633 | 72.70 | 0.62 | 14.39 | 2.05 | 0.011 | 0.00 | 0.12 | 4.18 | 5.84 | 0.074 |
| | **F10-22** | 17 | 427670 | 3697204 | 71.20 | 0.72 | 13.92 | 2.76 | 0.024 | 0.00 | 0.13 | 0.22 | 10.90 | 0.125 |
| | **F10-49** | 18 | 425895 | 3697678 | 70.43 | 0.69 | 14.43 | 1.46 | 0.013 | 0.13 | 0.02 | 0.28 | 12.46 | 0.076 |
| | **F10-81** | 19 | 421045 | 3696117 | 67.85 | 0.79 | 16.00 | 3.07 | 0.182 | 0.05 | 0.60 | 5.53 | 5.83 | 0.105 |
| | **F10-82A** | 20 | 422327 | 3698259 | 71.0 | 0.54 | 14.99 | 2.51 | 0.11 | 0.13 | 0.21 | 4.54 | 5.81 | 0.11 |
| | **F13-59** | 21 | 421001 | 3697921 | 67.39 | 0.77 | 15.87 | 3.17 | 0.172 | 0.54 | 0.75 | 5.54 | 5.68 | 0.105 |
| | **F13-87** | 22 | 423841 | 3695794 | 74.42 | 0.47 | 12.33 | 3.49 | 0.048 | 0.30 | 0.06 | 3.84 | 5.01 | 0.023 |
| **Alkali Granite dikes and plug, unit Ttag, various locations** | **F10-48** | 23 | 427276 | 3698609 | 69.67 | 0.67 | 14.53 | 3.02 | 0.013 | 0.07 | 0.53 | 2.76 | 8.64 | 0.088 |
| | **F10-76** | 24 | 423406 | 3696889 | 69.09 | 0.88 | 13.20 | 3.70 | 0.180 | 0.93 | 1.33 | 4.57 | 5.98 | 0.150 |
| | **F10-78** | 25 | 423813 | 3696364 | 66.21 | 0.77 | 16.42 | 3.39 | 0.231 | 0.50 | 0.45 | 6.42 | 5.45 | 0.154 |
| **Mafic Enclaves in Syenite** | **F13-68A** | 26 | 423222 | 3697580 | 55.8 | 2.08 | 15.39 | 8.97 | 0.37 | 2.72 | 4.40 | 5.81 | 3.39 | 1.05 |
| | **F13-76A** | 27 | 427815 | 3695325 | 57.9 | 2.09 | 16.75 | 8.33 | 0.27 | 1.61 | 2.31 | 5.39 | 4.39 | 1.01 |
| **Three Rivers Rhyolites, units Tog, Tcp and Tep** | **F09-120A** | 28 | 429896 | 3695793 | 72.1 | 0.37 | 15.19 | 1.82 | 0.03 | 0.17 | 0.14 | 2.18 | 8.01 | 0.03 |
| | **F10-52A** | 29 | 425828 | 3701568 | 78.5 | 0.19 | 10.00 | 2.36 | 0.03 | 0.02 | 0.06 | 0.22 | 8.62 | <0.01 |
| | **F10-71A** | 30 | 422713 | 3699411 | 72.4 | 0.63 | 13.75 | 2.87 | 0.12 | 0.08 | 0.28 | 5.10 | 4.68 | 0.10 |
| **Younger Dikes and Plug, units Ttbrd, Ttbhd, Tthbm** | **F09-118A** | 31 | 429849 | 3696650 | 69.7 | 0.68 | 16.43 | 1.71 | 0.01 | 0.13 | 0.24 | 5.71 | 5.24 | 0.09 |
| | **F10-77** | 32 | 423713 | 3696588 | 61.91 | 0.82 | 18.09 | 4.66 | 0.083 | 1.59 | 3.02 | 5.21 | 4.26 | 0.360 |
| | **F13-84** | 33 | 427426 | 3694720 | 63.96 | 0.96 | 17.24 | 4.27 | 0.123 | 1.14 | 2.16 | 5.70 | 4.16 | 0.287 |

1. The letter A after sample number means the analysis was made by ALS Laboratories. All others by LANL.

2. UTM locations NAD27, zone 13

TABLE 2. (Continued)

| Sample[1] | Fig. 2 location | Norm. total | Total alkalis | LOI | Raw total | Ba | Ce | La | Nb | Pb | Rb | Sr | V | Y | Zn | Zr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **F09-107A** | 532T | 100.03 | 11.41 | 0.70 | 98.37 | 1290 | 223 | 106 | 85.9 | 22 | 121 | 52.4 | 136? | 48.8 | 128 | 738 |
| **F13-78** | 532T | 100.00 | 11.48 | 0.60 | 99.137 | 1472 | 203 | 115 | 83 | 11 | 151 | 55 | 29 | 60 | 121 | 694 |
| **F13-79** | 532T | 100.01 | 11.32 | 0.91 | 98.840 | 1224 | 244 | 121 | 91 | 11 | 264 | 44 | 35 | 68 | 122 | 728 |
| **F13-80** | 532T | 99.99 | 11.69 | 0.40 | 99.327 | 1557 | 195 | 100 | 76 | 11 | 193 | 55 | 26 | 52 | 109 | 618 |
| **F13-81** | 532T | 99.99 | 11.26 | 0.94 | 98.796 | 1347 | 220 | 118 | 87 | 9 | 252 | 52 | 32 | 64 | 132 | 707 |
| **F10-25** | 1 | 100.001 | 11.77 | 0.32 | 99.419 | 1510 | 215 | 105 | 80 | 26 | 254 | 90 | 34 | 55 | 125 | 636 |
| **F10-63** | 2 | 100.000 | 10.93 | 1.42 | 98.334 | 1348 | 143 | 110 | 84 | 18 | 128 | 58 | 27 | 61 | 124 | 680 |
| **F10-73** | 3 | 100.005 | 10.98 | 0.85 | 98.598 | 4351 | 120 | 69 | 50 | 8 | 95 | 441 | 40 | 42 | 134 | 392 |
| **F10-75** | 4 | 100.008 | 11.36 | 0.55 | 99.195 | 1411 | 200 | 109 | 83 | 16 | 111 | 87 | 33 | 60 | 122 | 677 |
| **F10-80** | 5 | 100.001 | 11.40 | 0.40 | 99.378 | 1122 | 204 | 100 | 81 | 16 | 133 | 74 | 38 | 56 | 127 | 653 |
| **F13-58** | DCT | 99.98 | 11.16 | 0.19 | 99.587 | 767 | 234 | 107 | 102 | 9 | 147 | 120 | 23 | 73 | 74 | 842 |
| **F13-60** | DCT | 100.00 | 10.30 | 0.12 | 99.712 | 260 | 190 | 82 | 138 | 10 | 232 | 39 | 24 | 71 | 67 | 902 |
| **F13-61** | DCT | 100.00 | 10.97 | 0.18 | 99.577 | 537 | 381 | 192 | 125 | 10 | 220 | 83 | 30 | 104 | 122 | 1131 |
| **F13-62** | DCT | 99.99 | 11.34 | 0.33 | 99.447 | 702 | 404 | 222 | 105 | 6 | 167 | 131 | 30 | 55 | 50 | 848 |
| **F13-64** | DCT | 100.01 | 11.63 | 0.28 | 99.320 | 2842 | 370 | 202 | 76 | 7 | 145 | 185 | 45 | 77 | 105 | 426 |
| **F11-40** | TRT | 99.994 | 10.95 | 0.23 | 99.624 | 288 | 226 | 99 | 109 | 23 | 217 | 49 | 26 | 47 | 73 | 726 |
| **F11-39** | TRT | 100.009 | 11.08 | 0.14 | 99.689 | 422 | 270 | 134 | 105 | 30 | 226 | 71 | 26 | 64 | 65 | 677 |
| **F13-65** | TRT | 100.00 | 10.92 | 0.25 | 99.528 | 913 | 186 | 113 | 89 | 9 | 172 | 181 | 35 | 52 | 62 | 763 |
| **F13-66** | TRT | 100.01 | 10.48 | 0.27 | 99.421 | 2111 | 114 | 62 | 63 | 8 | 103 | 434 | 55 | 38 | 57 | 321 |
| **F13-67** | TRT | 99.99 | 11.12 | 0.40 | 99.349 | 1018 | 179 | 139 | 112 | 8 | 190 | 142 | 27 | 76 | 96 | 837 |
| **F11-15A** | TRT | 100.020 | 11.12 | 2.10 | 97.630 | 1890 | 223 | 132 | 99.5 | 31 | 170 | 140 | 33 | 49.0 | 148 | 647 |
| **F09-136A** | 6 | 99.97 | 11.14 | 0.80 | 97.61 | 567 | 221 | 99.8 | 121 | 38 | 177 | 65 | 28 | 50.4 | 117 | 948 |
| **NCP-18** | 7 | 99.997 | 11.58 | 0.57 | 99.236 | 400 | 209 | 68 | 111 | 23 | 229 | 46 | 43 | 66 | 58 | 986 |
| **F13-77** | EWT | 100.01 | 11.44 | 0.42 | 99.333 | 1353 | 229 | 109 | 88 | 9 | 134 | 56 | 32 | 59 | 124 | 695 |
| **F09-102A** | EWT | 99.960 | 10.99 | 1.70 | 96.480 | 1370 | 210 | 103 | 88.2 | 28 | 139 | 92.7 | 35 | 53.9 | 130 | 658 |
| **F13-83** | EWT | 100.01 | 11.57 | 0.39 | 99.319 | 1879 | 180 | 98 | 70 | 7 | 157 | 109 | 30 | 55 | 99 | 582 |
| **F13-89** | EWT | 100.00 | 11.18 | 0.39 | 99.346 | 1393 | 205 | 107 | 81 | 13 | 114 | 181 | 54 | 57 | 115 | 622 |
| **F13-86** | EWT | 100.00 | 11.18 | 0.69 | 99.060 | 963 | 261 | 136 | 99 | 14 | 194 | 129 | 45 | 63 | 54 | 879 |
| **F09-139A** | 8 | 99.98 | 11.50 | 0.39 | 99.05 | 1580 | 218 | 96.1 | 82.2 | 23 | 115 | 91 | 66 | 52 | 86 | 725 |
| **F10-74** | 9 | 99.993 | 11.49 | 0.21 | 99.501 | 1849 | 213 | 112 | 77 | 18 | 100 | 101 | 37 | 61 | 106 | 643 |
| **F10-86** | 10 | 100.011 | 11.11 | 0.45 | 99.298 | 1131 | 179 | 86 | 77 | 140 | 117 | 136 | 41 | 51 | 142 | 650 |
| **F13-88** | 11 | 100.01 | 10.67 | 0.58 | 99.141 | 1223 | 155 | 75 | 92 | 28 | 160 | 158 | 57 | 58 | 121 | 753 |
| **NCP-14** | 12 | 100.004 | 11.29 | 0.26 | 99.471 | 1291 | 191 | 121 | 85 | 14 | 114 | 100 | 43 | 62 | 113 | 677 |
| **F09-105A** | 13 | 99.96 | 11.20 | 0.60 | 96.72 | 507 | 248 | 119 | 113 | 27 | 528 | 21.3 | 7 | 57.8 | 23 | 991 |
| **F09-109** | 14 | 100.005 | 11.54 | 0.55 | 99.223 | 897 | 333 | 174 | 90 | 31 | 188 | 102 | 26 | 71 | 150 | 695 |
| **F09-135A** | 15 | 99.94 | 9.02 | 0.80 | 97.96 | 29.2 | 151 | 69 | 376 | 17 | 282 | 12.9 | 60 | 97.1 | 130 | 2850 |
| **F10-21** | 16 | 99.985 | 10.02 | 0.40 | 99.405 | 351 | 258 | 128 | 133 | 27 | 273 | 27 | 24 | 79 | 32 | 988 |
| **F10-22** | 17 | 99.999 | 11.12 | 0.92 | 98.838 | 644 | 191 | 102 | 100 | 24 | 658 | 36 | 28 | 66 | 121 | 826 |
| **F10-49** | 18 | 99.989 | 12.74 | 0.34 | 99.429 | 609 | 241 | 122 | 112 | 13 | 578 | 24 | 14 | 61 | 5 | 950 |
| **F10-81** | 19 | 100.007 | 11.36 | 0.75 | 99.015 | 850 | 431 | 233 | 92 | 30 | 188 | 115 | 26 | 71 | 141 | 817 |
| **F10-82A** | 20 | 99.95 | 10.35 | 0.90 | 96.71 | 389 | 215 | 93.8 | 98.9 | 29 | 224 | 59 | 50 | 41.1 | 94 | 715 |
| **F13-59** | 21 | 99.99 | 11.22 | 0.23 | 99.556 | 782 | 227 | 110 | 90 | 8 | 169 | 60 | 30 | 69 | 104 | 802 |
| **F13-87** | 22 | 99.99 | 8.85 | 0.64 | 99.141 | 20 | 287 | 127 | 226 | 33 | 254 | 7 | 21 | 101 | 95 | 1437 |
| **F10-48** | 23 | 99.991 | 11.40 | 0.62 | 99.180 | 410 | 170 | 131 | 115 | 24 | 395 | 27 | 25 | 66 | 102 | 843 |
| **F10-76** | 24 | 100.010 | 10.55 | 0.43 | 99.368 | 622 | 173 | 72 | 70 | 72 | 235 | 86 | 39 | 48 | 128 | 609 |
| **F10-78** | 25 | 99.995 | 11.87 | 0.30 | 99.553 | 249 | 179 | 75 | 62 | 72 | 200 | 25 | 32 | 36 | 154 | 506 |
| **F13-68A** | 26 | 99.98 | 9.20 | 1.09 | 97.80 | 2320 | 218 | 108 | 60.8 | 79 | 63.7 | 424 | 113 | 55.5 | 202 | 344 |
| **F13-76A** | 27 | 100.05 | 9.78 | 2.54 | 97.32 | 2140 | 298 | 157 | 80.1 | 20 | 108 | 282 | 79 | 70.2 | 237 | 396 |
| **F09-120A** | 28 | 100.04 | 10.19 | 2.00 | 97.42 | 251 | 129 | 77.8 | 106 | 27 | 292 | 99.7 | 155 | 43.1 | 78 | 548 |
| **F10-52A** | 29 | 100.00 | 8.84 | 1.00 | 95.53 | 53.2 | 73.7 | 26.6 | 157 | 12 | 498 | 26.3 | <5 | 64.7 | 20 | 915 |
| **F10-71A** | 30 | 100.01 | 9.78 | 1.37 | 96.72 | 190 | 234 | 115 | 90.6 | 49 | 163 | 80.7 | 57 | 50.6 | 94 | 846 |
| **F09-118A** | 31 | 99.94 | 10.95 | 1.27 | 96.49 | 634 | 70.9 | 60.5 | 97.3 | 19 | 157 | 103 | 33 | 38.8 | 31 | 855 |
| **F10-77** | 32 | 100.003 | 9.47 | 0.91 | 98.788 | 1627 | 108 | 70 | 67 | 26 | 94 | 681 | 76 | 16 | 65 | 334 |
| **F13-84** | 33 | 100.00 | 9.86 | 0.87 | 98.806 | 1918 | 124 | 77 | 48 | 10 | 83 | 574 | 62 | 40 | 89 | 413 |

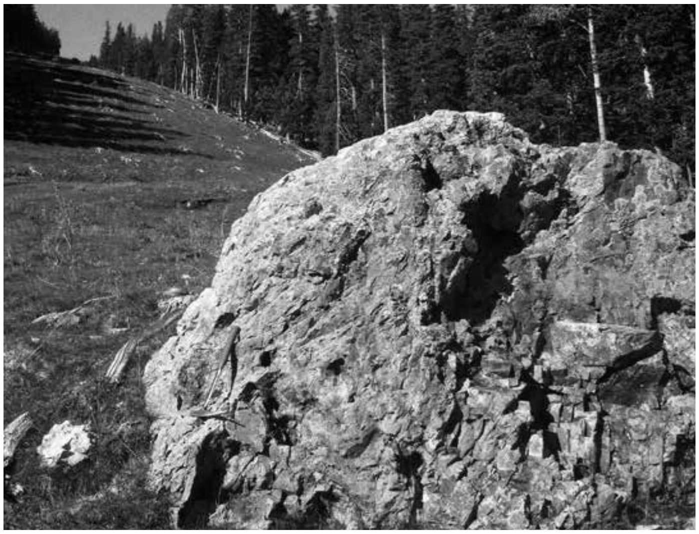

FIGURE 5. Stoped block of contact metamorphosed and silicified Sierra Blanca volcanics is exposed in a steep downhill run at Ski Apache (rock hammer for scale). Traceable across several runs, this 700-m-long block is surrounded by syenite (Tts) and alkali granite (Ttag). *(Photo by F. Goff)*


FIGURE 6. View north of west escarpment of Three Rivers stock shows roof pendant (P) of Sierra Blanca volcanics overlying alkali granite that in turn overlies quartz syenite. White dashed line is the trace of Dry Canyon Trail sampling traverse mentioned in text and shown in Fig. 2. *(Photo by F. Goff)*

slightly chilled margins. Alteration minerals consist of sericite, chlorite, Fe-oxides ± epidote, quartz or chalcedony, pyrite, and calcite. Quartz veins of varying width are common, particularly near the stock margins.

We dated a large anorthoclase phenocryst from the nordmarkite body southeast of Buck Mountain (Fig. 2) near contacts with medium-grained syenite (Tts) and alkali granite (Ttag). The $^{40}Ar/^{39}Ar$ age spectrum is considered fair; the age of 28.95 ±0.18 Ma is determined from four steps and probably represents the time at which the intrusion cooled below about 200 °C.

### Quartz Syenite to Alkali Granite, Unit Ttqs

A second large body of quartz syenite that locally grades into alkali granite occupies the west and southern part of the stock (unit Ttqs, Fig. 4B). The quartz syenite is generally medium-grained and gray to blue-gray or pale sandy gray in color. Many specimens have hypidiomorphic granular texture and contain large rounded blue-gray anorthoclase phenocrysts (usually ≤2 cm) sometimes rimmed with microperthite. Additional primary minerals consist of small K-feldspar, minor plagioclase, various amounts of interstitial quartz (some graphic texture), Na-amphibole, and biotite ± aegirine-augite and augite. Opaque oxides, zircon and sphene are usually present. Rutile, hematite and pyrite are rarely observed. The anorthoclase phenocrysts are most common in the eastern part of the unit at higher elevations, or at lower elevations in the southwest part of the unit. Most specimens display secondary quartz-sericite alteration. Mariolitic cavities are frequently found in the syenite, which contain quartz and black Na-amphibole or quartz and purple fluorite.

We dated an anorthoclase phenocryst from a sample of this unit on the Three Rivers Trail about 2 m east of the intrusive contact between volcanic country rock and syenite (Fig. 2). The $^{40}Ar/^{39}Ar$ age spectrum is noisy; the age of 28.24 ±0.19 Ma is determined from three steps and probably represents the time at which the intrusion cooled below about 200 °C.

### Syenite to Quartz Syenite, Unit Tts

A smaller body of syenite to quartz syenite, elongated in an east-west direction, intrudes the earlier, larger quartz syenite masses in the central and eastern portions of the stock. The contact between Tts (west) and Ttsp (east) crosses NM Highway 532 roughly 1 km west of Windy Point (Fig. 2). At this location the syenite is light gray to white, coarse-grained, hypidiomorphic granular and slightly porphyritic consisting of milky anorthoclase in a coarse groundmass of K-feldspar, quartz (some graphic), biotite, minor amphibole (<1%), and very minor plagioclase (0.5%). In thin section, the amphibole displays blue-green pleochroism and appears to be hornblende, not Na-amphibole. Accessory minerals consist of opaque oxides, apatite and zircon. Fine-grained, rounded mafic enclaves ≤8 cm long of monzonitic composition (see below) are commonly found in the syenite. Alteration consists of quartz-sericite, especially along alkali feldspar cleavage cracks, chlorite, Fe-oxides and minor epidote. We have not dated this unit.

### Very Coarse Syenite to Quartz Syenite, Unit Ttcs

Another type of syenite to quartz syenite is found as a somewhat large mass in the west-central part of the stock, but also forms several small, rounded, plug-like intrusions such as Lookout Mountain (Fig. 2). Rocks of this unit are distinctively gray, coarse-grained (minimum size of feldspar is 0.75 cm), and are hypidiomorphic granular consisting of a hash of abundant anorthoclase surrounded by smaller K-feldspar, quartz (some graphic), aegirine, Na-amphibole and sparse plagioclase (<0.5%). Accessory minerals are opaque oxides, apatite, and sparse rutile and zircon. Rounded mafic enclaves of fine-grained monzonitic rock are common in this unit (Fig. 4C, see below). Alteration minerals are generally quartz-sericite, Fe-oxides, chlorite and minor epidote. We did not date unit Ttcs.

### Alkali Granite, Unit Ttag

The most variable unit in the stock consists of alkali granite of various textures and mineral compositions, which appear as large irregular bodies and as smaller dikes, pods and plug-like masses. Most of the alkali granite is light gray and fine-grained (equivalent to the "equigranular syenite" of Giles and Thompson, 1972) consisting primarily of ±80% K-feldspar, interstitial quartz, minor biotite and no plagioclase. Some specimens contain a few percent of slightly larger K-feldspar crystals (Fig. 4A). Opaque oxides and apatite are usually present; zircon contents vary tremendously from virtually none to exceptionally abundant (>1%). The alkali granite grades into quartz syenite by progressive increase of K-feldspar and decrease of quartz. In the field, textural differences and relatively abundant quartz generally distinguish granite bodies from syenites. Mariolitic cavities are relatively common containing quartz and purple fluorite ± pyrite (Giles and Thompson, 1972, p. 2136). A small, plug-like mass of the fine-grained granite in the center of the stock was dated by $^{40}Ar/^{39}Ar$ at 27.19 ±0.21 Ma on biotite. The biotite age spectrum is somewhat disturbed with old apparent ages in the early and late steps. We are reporting the weighted mean age calculated from the middle five steps of the spectrum.

A 30-m broad, north-trending dike of alkali granite intrudes coarse-grained syenite in the west-central part of the stock. The granite has a medium-grained, hypidiomorphic granular texture and consists of K-feldspar (orthoclase), quartz (some graphic), Na-amphibole, biotite, opaque oxides and zircon. Slender Na-amphibole crystals project into some of the late-stage quartz. The granite is fresh in thin section; only a bit of sericite is present. The $^{40}Ar/^{39}Ar$ age of the dike is 27.74 ±0.10 Ma on K-feldspar.

The top of the eastern chair lift in Ski Apache sits on a 0.3-km wide body of medium-grained, hypidiomorphic granular alkali granite consisting of K-feldspar, abundant quartz (some graphic), aegirine, Na-amphibole, and minor biotite. Accessory minerals are opaque oxides and extremely abundant zircon (>1%, see section on Chemistry below). Alteration minerals are quartz-sericite-chlorite. Chemically, this is the most evolved granite analyzed. The $^{40}Ar/^{39}Ar$ age of this granite is the isochron age of 27 ±2 Ma on the amphibole. Probably, we should have dated the K-feldspar because the amphibole is interstitial and slightly altered.

### Mafic Enclaves

Mafic enclaves are most prevalent in the coarse-grained syenites (Tts and Ttcs, Fig. 4C) although a scant few were found in the nordmarkite (Fig. 4A). The enclaves are blob-shaped, sometimes shaped like fat "pancakes," and have fine-grained textures relative to their host, suggesting that mafic magmas were injected into and quenched within pre-existing syenitic melts (Didier and Barbarin, 1991; Stimac and Pearce, 1992; Goff et al., 2014, p. 96). The enclaves are generally ≤5 cm in diameter and make up <1% of the rock. Macroscopically, they are commonly weathered with formation of Fe-oxides at the expense of the mafic minerals. In thin section, the enclaves display fine-grained, equigranular texture, no vesicularity, and thin reaction rinds with host syenite. They consist of blocky plagioclase, augite ± hypersthene ± hornblende, opaque oxides and relatively abundant apatite (0.25%). Alteration minerals consist mostly of sericite, chlorite, and Fe-oxides.

### Rhyolites (Units Tep, Tcp and Tog)

Three types of rhyolite are found around the northern flanks of the Three Rivers stock. The largest body is the porphyritic rhyolite of Elk Point (unit Tep), which was first recognized as rhyolite by Segerstrom et al. (1979). The rhyolite is in fault contact with adjacent nordmarkite and, because of its porphyritic texture, was originally misidentified as syenite porphyry (Giles and Thompson, 1972). The rhyolite forms an irregular plug-like mass that intrudes a mixture of volcanic breccia and lava flows. The rhyolite consists of gray, coarsely porphyritic, partly flow-banded lava containing large sanidine phenocrysts in a groundmass of smaller K-feldspar, quartz, plagioclase, hornblende, biotite, opaque oxides, and tiny apatite in devitrified glass. The rhyolite only appears fresh at the west end of the intrusion, but even here, secondary quartz, sericite, chlorite and smudgy Fe-oxides affect the primary crystals, and the groundmass is partially silicified. Elsewhere, the rhyolite is the host of a large, slightly mineralized, hydrothermal breccia (Goff et al., 2011a). The "fresh" rhyolite is dated by $^{40}Ar/^{39}Ar$ at 28.19 ±0.15 Ma on sanidine.

The second rhyolite type (unit Tcp) consists of a group of small plugs and associated dikes of biotite rhyolite found just northwest of the stock (Fig 2; Cone Peak rhyolite of Black, 1977). Specimens contain small (<1 mm) phenocrysts of K-feldspar, quartz, biotite, and minor plagioclase in a highly silicified to potassic altered groundmass. The intrusions cut older volcanic rocks but not the Three Rivers stock. Because of the severe alteration and silicification, we did not date this unit.

The third type is the rhyolite sill of Oak Grove (unit Tog) located on the eastern flank of the stock just west of Oak Grove Campground. The rhyolite was previously mapped as a lava by Goff et al. (2011a) but on further scrutiny, it appears to be a sill of white, altered, aphyric rhyolite intruding highly altered, purple-red volcanic breccias. Thin section examination reveals extremely tiny microphenocrysts of quartz (<<0.01 mm) in a highly altered, flow banded, partly spherulitic groundmass. No other microphenocrysts are identifiable. The alteration products appear to be mostly kaolinite and other clays. No attempt was made to date this unit, although there are a few zones of "fresher" rock that might be dateable.

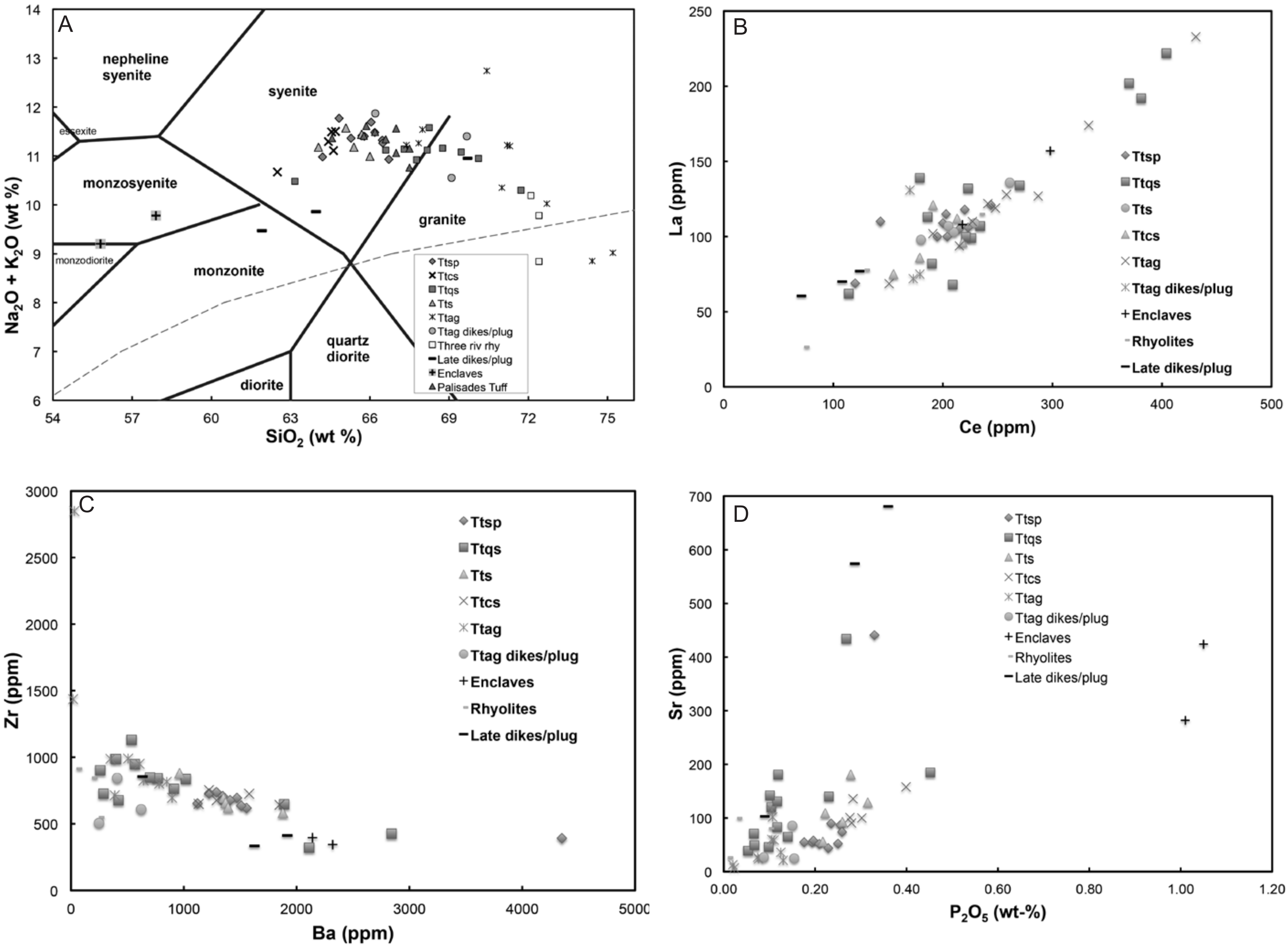


FIGURE 7. Geochemical plots of A. Total alkalis vs. silica (after Cox et al., 1979). The dashed red line separates alkaline (above) from sub-alkaline compositions. Unpublished data for the geochemically similar Palisades Tuff is also shown, B. La vs. Ce. C. Zr vs. Ba, and D. Sr vs. $P_2O_5$. See text for discussion of trends and relationships. Unit names are described in text and Figure 2.

### Late Small Intrusions (Units Ttbrd, Ttbhd and Tthbm)

We found three small intrusive bodies that post-date the emplacement of the stock. The first (unit Ttbrd) is a pair of north-east- to north-trending dikes of light gray biotite rhyolite that cut the nordmarkite and older volcanic rocks on the east margin of the stock. The southern dike forms a prominent rib at Texas Bend on NM 532 (Fig. 2). The dikes are about 2–3 m wide and consist of white, nearly aphyric, mildly altered rhyolite with sparse phenocrysts of K-feldspar and biotite in a silicified to devitrified groundmass containing tiny quartz (<0.1 mm), K-feldspar, and finely dispersed opaque oxides. K-feldspar phenocrysts are zoned and the entire rock is mildly seriticized. Biotite from the southern dike is dated by $^{40}Ar/^{39}Ar$ at 25.4 ±0.8 Ma.

The second late intrusive (Ttbhd) is a WNW-trending dike of greenish gray biotite-hornblende trachyte that is also about 2–3 m wide. This dike is observable at the junction of NM 532 and the dirt road to Buck Mountain and can be followed for nearly a kilometer. The trachyte contains phenocrysts of complexly zoned plagioclase, augite, hornblende, biotite, rare small K-feldspar (1 mm), opaque oxides, and apatite in a felty groundmass of plagioclase, augite, opaque oxides and devitrified glass. We did not date this dike although the biotite looks fresh enough to do so.

The third late intrusive is a small plug of fresh-looking monzonite only 50 m in diameter exposed in the center of the stock west of Ski Apache. The monzonite is white to light gray, containing larger crystals of K-feldspar, hornblende and biotite in a groundmass of plagioclase, augite, and a little quartz. Accessories include opaque oxides, apatite and rare zircon. The monzonite was initially mapped as a syenite plug by Goff et al. (2011a) but chemistry described below shows it is monzonite. The monzonite intrudes syenite (Tts) and a small stoped block of older, metamorphosed trachyandesite to trachybasalt. Biotite from the monzonite plug is dated by $^{40}Ar/^{39}Ar$ at 25.91 ±0.26 Ma. The age is the weighted mean age of only two heating steps but is based on about 90% of the released $^{39}Ar$.

## CHEMICAL VARIATIONS IN THREE RIVERS STOCK

### Syenite Chemistry

The two oldest and largest intrusive bodies in the Three Rivers stock consist of nordmarkite (quartz syenite porphyry, unit Ttsp) and medium-grained quartz syenite to alkali granite (unit Ttqs). We analyzed 23 samples from these two units to examine possible vertical and spatial variations in chemistry (Table 2 and Fig. 2). We analyzed five samples of nordmarkite in a traverse (labeled 532T, Fig. 2) beginning southeast of Buck Mountain and extending down the east margin of the intrusion to its contact with volcanic country rock, an elevation drop of 450 m. Amazingly, there is practically no change in the chemistry of Ttsp along this traverse except for the relative amounts of $Na_2O$ and $K_2O$ (Fig. 7A). Even so, the total alkali contents are more or less constant at roughly 11.45 ±0.2 wt-%. We see a small increase in $SiO_2$ and small decreases in MgO and CaO going from high elevation to low. Five additional samples of nordmarkite were analyzed from widely distributed sites in the north and west parts of the unit. Four of the five analyses resemble those from the traverse. One sample, F10-73 from near the west contact has noticeably less $SiO_2$, but more $Al_2O_3$ and significantly more Ba (the most Ba of any sample we analyzed). Other trace element contents are also different from "typical" nordmarkite. This sample has less anorthoclase phenocrysts than other nordmarkite samples and is also located near a zone of hydrothermal breccia on the west edge of the stock.

Two vertical chemical traverses were made through the west part of the medium-grained quartz syenite (unit Ttqs) where it is exposed along the west escarpment of the Sierra Blanca. The first traverse consisting of five analyses follows the trail along Dry Canyon (Figs. 2 and 6, DCT) from the contact (elevation of 2560 m) of Ttqs with adjacent and overlying alkali granite (Ttag) down to the intrusive contact of Ttqs with older volcanic lava flows (Fig. 4D). This represents a vertical drop of 220 m. Unit Ttqs is more variable in its chemistry than unit Ttsp. The upper samples of the Dry Canyon traverse lie at the chemical boundary between alkali granite and syenite (Fig. 7A) while the lower samples clearly have syenite composition. The Three Rivers Trail traverse (Fig. 2) consists of six samples that represent a vertical drop of 475 m from the contact (elevation of 2680 m) of adjacent alkali granite (Ttag) down to the contact with older lava flow breccia. As with the previous traverse, higher elevation samples on the Three Rivers Trail traverse are borderline alkali granite while lower elevation samples are syenitic. Sample F13–66 comes from the mouth of Fall Creek at an elevation of 2280 m. This sample is noticeably less evolved than other samples in the traverse, resembling the lowest elevation sample from the Dry Canyon traverse. It is also spatially closer to the core of the stock. In both traverses, $SiO_2$ decreases downwards (Table 2) but there are systematic increases in most of the major elements, including total alkalis, and systematic increases in Ba, La, Sr, V, Zn and possibly Ce. In contrast, Nb and Zr decrease downwards. We conclude that in a vertical sense, unit Ttqs represents a "zoned" magma body in which the most silicic and evolved magma is at the top, and the more mafic magma is at the bottom (Smith and Bailey, 1966; Lipman, 2000).

We analyzed two other samples of unit Ttqs (Table 2). Samples F09-136 and NCP-18 (elevations of roughly 3250 m) come from the Ski Apache area in the north-central part of the unit. Their chemical analyses resemble the higher elevation analyses from the two traverses discussed previously.

We analyzed five samples of coarse-grained syenite, unit Tts in a southwest-northeast traverse (EWT, Fig. 2) stretching from near the east margin to the west-central portion of the stock (4.5 km) in which elevations are rather constant at 3050 to 3170 m. Along this traverse, we observe small increases in Mg, Ca, Rb, Sr, Ce, La and Zr, but small decreases in Ba and Zn. Five samples of very coarse-grained syenite, unit Ttcs, were also analyzed. As a group these five are chemically the least evolved on average but they resemble other less evolved syenites in the stock.

### Alkali Granite Chemistry

As mentioned before, the alkali granites are texturally the most variable group of rocks in the stock and also display interesting chemical variations. Taken as a whole they range from borderline syenitic to extremely granitic in composition (66.2 to 75.2 wt-% $SiO_2$). Most of the samples have roughly equal amounts of $Na_2O$ and $K_2O$, but four of them are exceptionally rich in $K_2O$ and low in $Na_2O$, (samples F09-105, F10-22, F10-49 and F10-48) with ranges of 8.6 to 12.5 wt-% $K_2O$ and 0.22 to 2.8 wt-% $Na_2O$. Trace element contents of these four samples are quite average for the alkali granite group. In the field, these samples do not display unusual alteration. In thin section, they consist solely of orthoclase, quartz, biotite and minor opaque oxides. The two most silicic samples of the alkali granite group are also unusual, samples F09-135 and F13–87. These two have the lowest $TiO_2$ (<0.5 wt-%), Ba (≤30 ppm) and Sr (≤13 ppm), but the highest Nb (≥226 ppm), Y (≥97 ppm) and Zr (≥1440 ppm). Sample F09-135 has about twice as much Zr as any other samples we analyzed, 2850 ppm.

### Mafic Enclave Chemistry

Two mafic enclaves were analyzed, one (F13–68) from the main body of very coarse-grained syenite (Ttcs, sample point 26, Fig. 2) and the other (F13–76) from the coarse-grained syenite (Tts) at its contact with nordmarkite along NM 532 (sample point 25). Although less rich in $SiO_2$ than the syenites, they are still relatively alkaline (≥9.2 wt-% total alkalis) and plot as monzodiorite to monzosyenite (Fig. 7A). Relative to the syenites, the enclaves contain high Ti, Fe, P, Ba, Sr, and Zn but less Rb and Zr. The enclaves are slightly more alkalic than equivalent intrusive rocks in the Bonito Lake and Rialto stocks (see Goff et al., 2011a, fig. 10). Had these magmas erupted at the surface as lava flows, they would be classified as trachyandesite (La Bas et al., 1986). Considerable amounts of trachyandesite were erupted in the Sierra Blanca volcanics, which predate the Three Rivers stock (Thompson, 1972; Goff et al., 2011a), but the existence of abundant enclaves in the syenite indicates that this alkalic magma type was still present at depth after the syenitic melts were formed.

### Rhyolite Chemistry

As mentioned before, three rhyolite units flank the north and east sides of the Three Rivers stock (Fig. 2). The sill of aphyric rhyolite (unit Tog, F09-120) contains very high $K_2O$ (8 wt-%) and low $Na_2O$ (2.2 wt-%), resembling four of the potassium-rich alkali granites within the northeast part of the stock. The similarity seems more than fortuitous and suggests the Oak Grove rhyolite is genetically related to potassic alkali granite magmatism in the stock. The second rhyolite (Tcp) is from a tiny plug with radiating dikes in the Cone Peak area. This rock is also rich in $K_2O$ but the matrix looks silicified and altered, resulting in high $SiO_2$ (78.5 wt-%), and low Al and possibly Na. The third rhyolite is the porphyritic unit from Elk Point (Tep), which resembles most of the alkali granites by having roughly equal amounts of $Na_2O$ and $K_2O$ (Table 2).

### Late Small Intrusions Chemistry

The three later intrusions consist of a tiny plug of monzonite, and dikes of trachyte and rhyolite (Fig. 7A). As a group, they apparently form a linear chemical trend. The rhyolite dike resembles the composition of the alkali granites. The monzonite plug and trachyte dike are different than other Three Rivers units but they are similar in composition to evolved units in the Bonito Lake and Rialto stocks (Goff et al., 2011a, fig. 10) and they have similar ages. Dates of 25.9 to 25.4 Ma were obtained for two of the young intrusions. Thus, it is possible that the younger intrusions in Three Rivers stock are part of a broader phase of younger magmatism to the north (Fig. 1).

### Trace Element Variations

Since the 1970s, improved analytical methods and reduced costs have made trace element analyses widely available as a geochemical tool for igneous petrology (e.g., Wilson, 1989, p. 15–34). The data in Table 2 provide a snapshot of trace element variations in the Three Rivers stock and will be discussed in more detail in another paper. However, there are a few elements that display wide variations in concentration and deserve some initial comments.

First, rare earth elements (REE), of which La and Ce are generally most common in igneous rocks, are of significant economic importance to the world economy and are often enriched in syenitic and alkalic rocks (McLemore et al., 1988; Kramer, 2010; Folger, 2011; Gleason, 2011). Although concentrations of REE in the Three Rivers stock are not particularly high (Goff et al., 2011a), La and Ce are positively correlated, forming a very linear trend (Fig. 7B). Four of the quartz syenite and alkali granite samples have considerably more La and Ce than other samples. Curiously, these four samples all occur on the northwest side of the stock. Most of the rhyolites and all the late dikes and plug samples have low La and Ce.

Second, there is a strong negative correlation between Zr and Ba (Fig. 7C). Zr is a classic "incompatible" element that is generally concentrated as zircon in felsic igneous rocks. Ba is often enriched in mafic igneous rocks, substitutes for K in K-feldspar, and is mobilized in hydrothermal systems (Wilson, 1989). Two samples of syenite have more than 2500 ppm Ba and may have been subjected to hydrothermal alteration. Ignoring these two samples, those with the most Ba are the enclaves, a couple of the syenites, and two late intrusions (the monzonite plug and the trachyte dike). On the other end of the spectrum, the two alkali granites with the most silica (Table 2) also have by far the most Zr (>1400 ppm) and the least Ba (<30 ppm).

Finally, Sr is generally concentrated in plagioclase and P in apatite. These two minerals are most common in relatively mafic rocks. Figure 7D shows that most of the units in the stock have only modest quantities of Sr and $P_2O_5$ (mostly <200 ppm, and <0.50 wt-%, respectively) but also shows two possible trends.

One is a trend toward the compositions of the mafic enclaves, which are relatively rich in $P_2O_5$ and the other is a trend toward the compositions of the late monzonite and trachyte intrusions, which are rich in Sr. Most of the syenites from units Ttsp, Tts and Ttcs lie on the former trend and, as pointed out above, units Tts and Ttcs have visible enclaves (e.g., Fig. 4C). These units are mostly found in the south and west parts of the stock. In contrast, most of the syenites from unit Ttsp (the nordmarkite) and all the rhyolites lie on the second trend. These units are found in the north and east parts of the stock. Thus, there seems to be some spatial influence to the magma compositions and their genesis within the stock.

## CONCLUSIONS

Several observations suggest that the Three Rivers stock represents the unroofed intrusive complex beneath a small (≤12–km-diameter), eroded caldera. First, the stock is roughly circular in plan, slightly elongated in a southwest-northeast direction. The top and upper portions of the intrusive complex contain abundant stoped blocks and roof pendants of contact metamorphosed older country rocks. The oldest major intrusive bodies (syenite to quartz syenite) are slightly older and less chemically evolved than the younger, less voluminous alkali granites. The granitic magmas possibly fed post-caldera rhyolite eruptions that are now eroded away and/or contributed to uplift of a small post-caldera resurgent dome (Smith and Bailey, 1968). Three types of rhyolite that are geochemically similar to the alkali granites flank the northern margins of the stock. One of them, Elk Point, is dated at 28.2 Ma, which falls chronologically between the syenites (29 to 28 Ma and alkali granites (27.7 to 27 Ma). This indicates to us that the rhyolites may be the eroded remnants of ring-fracture volcanism surrounding the northern margins of the stock. Finally, two geochemical traverses down the uplifted western margin of one of two major intrusive bodies show that syenites at the top of the stock are more evolved (silicic) than syenites at the bottom. This suggests that the intrusive complex is normally zoned, a geochemical characteristic of most magma chambers beneath calderas (Smith and Bailey, 1966; Lipman, 2000).

The Three Rivers stock has been previously identified as the exhumed root of a small caldera based on indirect evidence from an earlier study (Goff et al., 2011b). The major syenitic bodies of the stock are geochemically similar to the Palisades Tuff, a recently recognized trachytic ignimbrite located roughly 10 km west of the stock in the Godfrey Hills, Tularosa Basin (Fig. 1). Sanidine phenocrysts in the tuff are dated at 28.67 ±0.07 Ma (average of two samples), yielding an age similar to those of the large syenite bodies. The primary mineral assemblage of the tuff consists of sanidine, quartz, minor plagioclase, augite, and biotite, remarkably similar to the minerals in the syenites. Importantly, the fiamme and groundmass of the tuff contain Na-amphibole, a late-stage constituent in the interstices of the syenites. Thus, based on direct and indirect evidence, we conclude that the Three Rivers stock is the intrusive complex beneath a now eroded caldera that erupted the Palisades Tuff. If true, it is our opinion that at least 3 km of roof rock has been eroded off the top of the stock. All intracaldera rocks and near-surface caldera structures are missing.

## ACKNOWLEDGMENTS

We are indebted to S.A. Kelley, J.R. (Rick) Lawrence, C. Cikoski, and D. Krier who co-authored the geologic map of the Nogal Peak 7.5-minute quadrangle. This paper was sponsored by the National Cooperative Geologic Mapping Program, with U.S. Geological Survey and NMBGMR funding. Additional funding came from Otero Soil and Water Conservation District. A New Mexico Small Business Assistance Program grant #10783 through LANL paid for fieldwork by R.C. Roback and chemical analyses by E.C. Kluk (Group EES-14). Diana Brown (post baccalaureate student in EES-14) helped prepare the chemistry samples. Lisa Peters (NMBGMR) determined the rough Ar/Ar dates. Stephanie Chavez (NMBGMR) constructed Figure 2. Professor Claus Siebe, Instituto de Geofísica, UNAM, Mexico and Don Hickmott (LANL) provided constructive reviews of the draft manuscript. A final round of reviews and editorial comments were obtained from N. Dunbar, G. Rawling, and V. McLemore of NMBGMR.

## REFERENCES

Allen, M.S., and Foord, E.E., 1991, Geological, geochemical, and isotopic characteristics of the Lincoln County Porphyry Belt, New Mexico: Implications for regional tectonics and mineral deposits: New Mexico Geological Society, Guidebook 42, p. 97–113.

ALS Laboratory Group, 2011, Schedule of services and fees: ALS Chemex, Mineral Division, Vancouver, Canada, 40 p., www.alsglobal.com, accessed 5/7/14.

Black, K.D., 1977, Petrology, alteration, and mineralization of two Tertiary intrusives, Sierra Blanca igneous complex, New Mexico [M.S. thesis]: Fort Collins, Colorado State University, 124 p.

Cox, K.G., Bell, J.D., and Pankhurst, R.J., 1979, The Interpretation of Igneous Rocks: Allen and Unwin, London, 450 p.

Didier, J., and Barbarin, B., 1991, The different types of enclaves in granites – nomenclature, *in* Didier, J. and Barbarin, B., eds., Enclaves and Granite Petrology: Developments in Petrology, v. 13, Elsevier, Amsterdam, p. 19–23.

Folger, T., 2011, The secret (Chinese) ingredients of (almost) everything: National Geographic, June, p. 136–145.

Giles, D.L., and Thompson, T.B., 1972, Petrology and mineralization of a molybdenum-bearing alkalic stock, Sierra Blanca, New Mexico: Geological Society of America, Bulletin, v. 83, p. 2129–2148.

Gleason, W., 2011, Mountain Pass Mine: At the heart of the rare earths resurgence: Mining Engineering, v. 63, p. 33–37.

Goff, F., Kelley, S.A., Lawrence, J.R., Cikoski, C., Krier, D.J., Goff, C.J., and McLemore, V.T., 2011a, Preliminary geologic map of the Nogal Peak quadrangle, Lincoln and Otero counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map, OF-GM 134, 1:24,00 scale 82 p.

Goff, F., Dunbar, N., Kelley, S.A., Peters, L., McIntosh, W., Heizler, L.L., and Goff, C.J., 2011b, Three Rivers stock and Palisades Tuff: Correlating intrusive source with ignimbrite sheet in the tectonically disrupted Sierra Blanca igneous complex, New Mexico (abs.): Geological Society of America, Annual Meeting, Abstracts with Programs, v. 43(5), p. 651.

Goff, F., Warren, R.G., Goff, C.J., and Dunbar, N., 2014, Eruption of reverse-zoned upper Tshirege Member, Bandelier Tuff from centralized vents with Valles caldera, New Mexico: Journal of Volcanology and Geothermal Research, v. 276, p. 82–104.

Govindaraju, K., 1994, Compilation of working values and sample description for 383 geostandards: Geostandards Newsletter, v. 18, p. 15–35.

Koning, D.J., Kelley, S.A., and Goff, F., 2014, Preliminary Geologic Map of the Northeastern Tularosa Basin and Western Sierra Blanca Basin, Lincoln and Otero Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 564.

Kramer, D., 2010, Concern grows over China's dominance of rare-earth metals: Physics Today, May, p. 22–24.

La Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Lipman, P.W., 2000, Calderas. *In*: Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., Stix, J., eds., Encyclopedia of Volcanoes: Academic Press, San Diego, p. 643–662.

McLemore, V.T., North, R.M., and Leppert, S., 1988, Rare-earth elements (REE) in New Mexico: New Mexico Geology, v. 10, p. 33–38.

McLemore, V.T., Goff, F., and McIntosh, W., 2014, Geology, mineral resources and environmental assessment of the Nogal-Bonito mining district, Sierra Blanca, Lincoln County, New Mexico: New Mexico Geological Society, Guidebook 65.

Moore, S.L., Foord, E.E., Meyer, G.A., and Smith, G.W., 1988, Geologic map of the northwestern part of the Mescalero Apache Indian Reservation, Otero County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1895, 1:24,000 scale.

Moore, S.L., Thompson, T.B., and Foord, E.E., 1991, Structure and igneous rocks of the Ruidoso region, New Mexico: New Mexico Geological Society, Guidebook 42, p. 137–145.

Paterson, S.R., Vernon, R.H., and Fowler, T.K., 1991, Aureole Tectonics, *in* Kerrick, D.M., ed., Contact Metamorphism - Reviews in Mineralogy: Mineralogical Society of America, v. 26, Washington, D.C., p. 673–722.

Rigaku Corporation, 2009, ZSX Primus Series Instruction Manual.

Segerstrom, K., Stotelmeyer, R.B., Williams, F.E., and Cordell, L., 1979, Mineral resources of the White Mountain Wilderness and adjacent areas, Lincoln County, New Mexico: U.S. Geological Survey, Bulletin 1453, 135 p.

Smith, R.L., and Bailey, R.A., 1966, The Bandelier Tuff: A study of ash-flow eruption cycles from zoned magma chambers: Bulletin of Volcanology, v. 29, p. 83–103.

Smith, R.L., Bailey, R.A., 1968, Resurgent cauldrons: Geological Society of America Memoir 116, 613–662.

Stimac, J.A., and Pearce, T.H. 1992, Textural evidence of mafic-felsic magma interaction in dacitic lavas, Clear Lake, California: American Mineralogist, v.77, p. 795–809.

Thompson, T.B., 1966, Geology of the Sierra Blanca, Lincoln and Otero Counties, New Mexico [Ph.D. dissertation]: University of Michigan, Ann Arbor, 205 p.

Thompson, T.B., 1972, Sierra Blanca igneous complex, New Mexico: Geological Society of America Bulletin, v. 83, p. 2341–2356.

Thompson, T.B., 1973, Mineral deposits of Nogal and Bonito mining districts, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 123, 29 p.

Williams, H., Turner, F.J., and Gilbert, C.M., 1954, Petrography: W.H. Freeman and Co., San Francisco, 406 p.

Wilson, M., 1989, Igneous Petrogenesis: Unwin Hyman, London, 466 p.

Woodward, L.A., 1991, Tectono-metallogenic maps of mining districts in the Lincoln County Porphyry Belt, New Mexico: New Mexico Geological Society, Guidebook 42, p. 283–290.

Geologists and packers saddling up horses near uppermost Bonito Creek in the White Mountain Wilderness. *Photo courtesy of Fraser Goff.*