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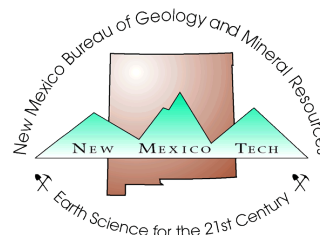
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Rb, Sr, Rb–Sr, and isotopic Sr values for volcanic rocks from the southwestern part of the Mogollon–Datil volcanic field

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Introduction

As part of an on-going geochemical study of the western part of the Mogollon–Datil volcanic field of southwestern New Mexico, 55 samples originally collected for K–Ar dating were analyzed for rubidium and strontium content by x-ray fluorescence, and 30 of these samples were selected for isotopic Sr analysis. These results are combined with published results in this paper. The purpose of the study is to use Rb and Sr concentrations and isotopic Sr ratios to help determine the origin of the volcanic rocks.

The western part of the mid-Cenozoic Mogollon–Datil volcanic field is dominated by three major intersecting calderas (Fig. 1), which form the Mogollon Mountains. The timing of the caldera collapses as given by conventional K–Ar dates (Ratté et al., 1984; Marvin et al., 1987) and by $^{40}\text{Ar}/^{39}\text{Ar}$ dating (McIntosh et al., 1986; McIntosh, 1989) sug-

gests that the Mogollon caldera was active from 35.5 to 33 m.y. ago and the Gila Cliff Dwellings and Bursum calderas from 30 to 26 m.y. ago. The oldest of the calderas, the Mogollon caldera is associated with the eruption of the 33–34 m.y. old Cooney Tuff. The distribution of the ca. 29 m.y. old Shelley Peak and Davis Canyon Tufts suggests a source within the Mogollon Mountains area, possibly the Gila Cliff Dwellings caldera, prior to the collapse of the younger Bursum caldera. The Bursum Caldera was produced in response to the eruption of the voluminous Bloodgood Canyon Tuff, and in turn was filled by the Apache Spring Tuff during continued subsidence.

Previous geological and geochemical studies in the Mogollon–Datil volcanic field are reviewed in: Elston and Northrop (1976), Osburn and Chapin (1983), Elston (1984), and Ratté et al. (1984). Additional chemical data

are found in Ratté and Grotbo (1979), in the dissertation of Bornhorst (1980), and the thesis of New (1981). Rb and Sr analyses, as part of isotopic Sr studies, have been reported in abstracts by Bikerman (1976), Stinnett and Stueber (1976), Bikerman and Bell (1986), Ruiz et al. (1986); in a dissertation by Stinnett (1980), whose Rb and Sr abundance and isotopic data are summarized in Table 1A and 1B; and in papers by Bornhorst and Brookins (1983) and Eggleston and Norman (1986). Isotopic data published prior to 1987 are incorporated into the geochronologic compilation of Marvin et al., (1987).

Experimental procedures

K–Ar dating on felsic and intermediate rocks was done on biotite, sanidine, or other mineral separates; mafic rocks were dated on whole-rock samples.

Conventional mineral-separation procedures were used on these samples. Sieved washed samples underwent some combination of magnetic, density, and grain-flatness separation. All intermediate steps of partial separation were saved routinely for use in further separation or other studies. These intermediate products are the partial separates used in the isotope-dilution Rb–Sr isochron dates in this paper.

The x-ray fluorescence (XRF) determinations of Rb and Sr and the isotopic data ($^{87}\text{Rb}/^{86}\text{Sr}$, $^{87}\text{Sr}/^{86}\text{Sr}_m$, and $^{87}\text{Sr}/^{86}\text{Sr}_i$, and K–Ar dates) are shown in Table 2. The K–Ar dates used in the calculation of the $^{87}\text{Sr}/^{86}\text{Sr}_i$ (initial ratio) were determined in the University of Pittsburgh laboratory, with the exceptions of the Davis Canyon Tuff (H9–77) for which the $^{40}\text{Ar}/^{39}\text{Ar}$ date in McIntosh et al. (1986) was used

TABLE 1A—Rb and Sr contents in four rock types (Stinnett, 1980). (Number of samples used to determine the averages listed.)

Rock type	Rb (ppm)	Range	Sr (ppm)	Range	Rb/Sr range
basalt (12)	25 ± 13	11–55	709 ± 286	279–1140	0.02–0.07
basaltic andesite (16)	82 ± 42	33–130	790 ± 109	625–991	0.03–0.18
andesite (37)	85 ± 23	46–140	651 ± 117	437–903	0.07–0.25
felsite (11)	119 ± 43	62–200	377 ± 91	210–530	0.14–8.2

TABLE 1B—Initial Sr ratios (Stinnett, 1980) for rock units in the study area.

Formation (rock type)	$^{87}\text{Sr}/^{86}\text{Sr}_i$
Bearwallow Mtn (andesite) (8)	0.7078–0.7083
John Kerr Peak (latite) (1)	0.7067
Wall Lake (andesite) (1)	0.7078
Double Springs (basalt) (1)	0.7079

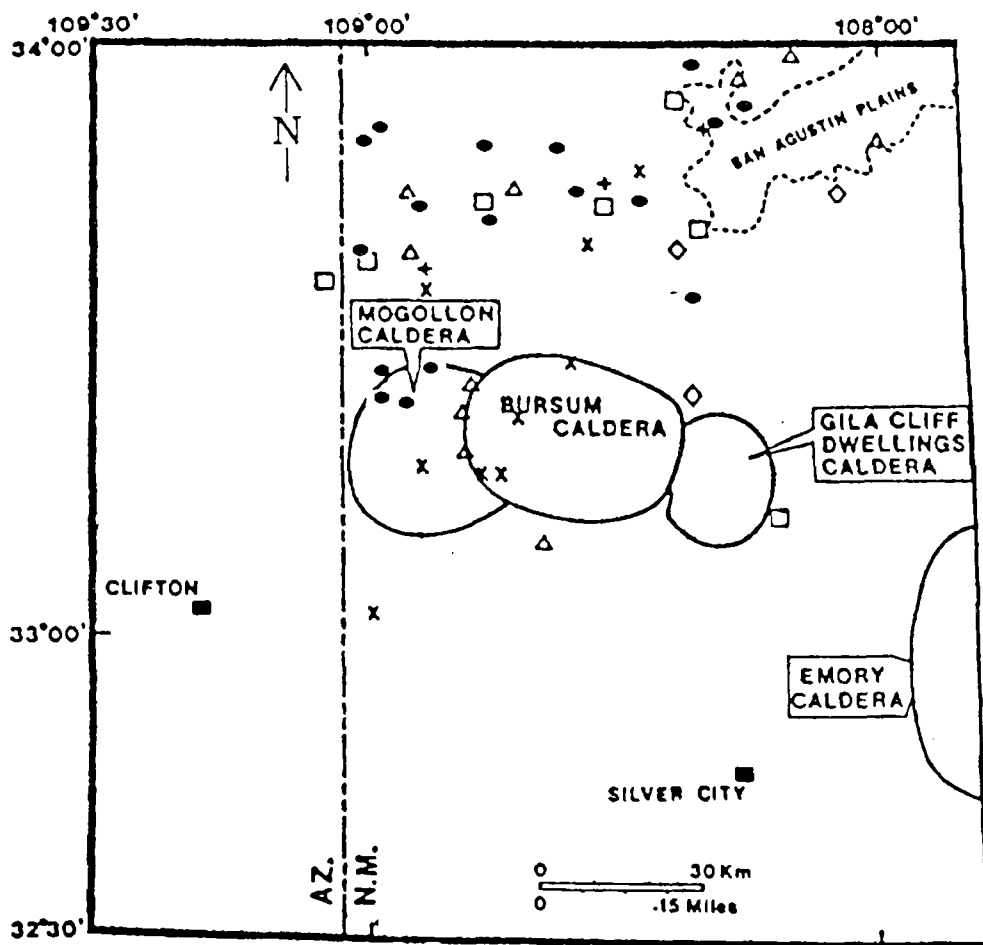


FIGURE 1—Location of samples collected for this study. The caldera outlines are from Ratté et al. (1984).

TABLE 2—Rb and Sr contents, K–Ar dates, and Sr isotopic data for rocks from the Mogollon–Datil volcanic field. *, data from Bornhorst and Brookins (1983) and **, data from Stinnett (1980) recalculated to new constants; SID, isotope dilution analyses from Scottish Universities Research and Reactor Centre (Bikerman, 1976; Marvin et al., 1987); CID, isotope dilution analyses from Carleton University, 1985; all other Rb and Sr analyses by XRF from Carleton University, 1985. Data in parentheses indicate estimates because no K–Ar dates are available; blank spaces indicate no determinations. References refer to stratigraphic nomenclature.

Sample	Latitude, Longitude	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	K–Ar date (m.y.)	⁸⁷ Sr/ ⁸⁶ Sr _m	⁸⁷ Sr/ ⁸⁶ Sr _i
Bloodgood Canyon Tuff (Elston, 1968; Ratté et al., 1984)							
G-48	N33°43'39", W108°34'34"	243.0	36.8	19.1	27.3	0.71671	0.70930
G-35	N33°43'09", W108°47'11"	268.0	83.2				
G-7A	N33°40'27", W108°21'20"	230.0	80.1	8.3	28.3	0.71321	0.70987
G-24	N33°56'00", W108°25'20"	259.0	23.0	33.1	28.5	0.72255	0.70918
M675	N33°11'22", W108°10'45"	249.0	43.8	16.4	26.9	0.71619	0.70990
G-51	N33°38'38", W109°01'09"	256.0	24.3	30.5	27.3	0.72228	0.71045
G-23	N33°36'49", W109°05'28"	297.0	21.7	39.7	28.3	0.72463	0.70869
" replicate		302	22.5				
" (SID)		266.0	20.0	38.53	28.3	0.72477	0.70928
" (CID)		272.2	20.9	37.75	28.3	0.72463	0.70946
G-33	N33°43'22", W108°47'06"	330	14.2				
*76T16	N32°12'02", W108°19'13"	260.0	18.5	40.7	27.8	0.7232	0.70713
Shelley Peak Tuff (Ratté et al., 1972, 1984)							
G-15A	N33°45'58", W108°32'30"	188.0	171.0	3.2	28.7	0.70944	0.70815
G-15B		199.0	183.0	3.2	28.7	0.70969	0.70841
G-26	N33°52'48", W108°19'13"	154.0	245.0	1.8	31.7	0.70957	0.70876
G-58	N33°38'31", W109°01'07"	181.0	193.0	2.7	30.1	0.71035	0.70919
G-73	N33°36'27", W108°53'42"	213.0	105.0				
*76T79	N33°32'27", W108°56'03"	210.0	212	2.9	28.2	0.7112	0.71010
Other felsic rocks							
Jerky Mountains Rhyolite (Elston, 1968)							
G-6A	N33°39'40", W108°23'24"	270.0	6.2	126.6	26.2	0.76219	0.71507
ARS	N33°23'48", W108°22'32"	254.0	32.8	22.4	27.7	0.71885	0.71003
Rhyolite of Shaw Canyon (Willard and Stearns, 1971)							
G-46	N33°45'35", W108°04'17"	221.0	4.7	137.0	28.5	0.78418	0.7287
Mule Mountain Rhyolite (Weber and Bassett, 1963; Rhodes and Smith, 1972; Marvin et al., 1987)							
*R526	N33°07', W108°52'	238.0	21.0	32.8	18.6	0.7193	0.71064
Rhyolite from Horse Mountain volcano (Bornhorst, 1980; Marvin et al., 1987)							
*T-274	N33°59'19", W108°04'29"	146.0	166.0	2.5	~19	0.7090	0.7083
Cooney Quartz Latite (Ferguson, 1927) or Cooney Tuff (Ratté, 1981)							
G-8	N33°25'18", W108°49'26"	317.0	104.0	8.8	34.0	0.71534	0.71108
G-9	N33°22'30", W108°48'31"	213.0	108.0	5.7	33.1	0.71326	0.71057
Tuff Breccia of Horse Springs (Lopez, 1975)							
G-31	N33°55'10", W108°15'29"	177.0	217.2	2.36	32.2	0.71106	0.70999
" (CID)		184.4	231.1	2.31	32.2	0.71087	0.70981
Davis Canyon Tuff (Ratté et al., 1972, 1984)							
G-32	N33°37'20", W108°53'30"	214.0	63.2	9.8	29.0	0.71383	0.70980
H9-77	N33°50'01", W108°00'45"	230.0	42.2	15.8	29.03	0.71464	0.70814
Tularosa Canyon rhyolite (Rhodes, 1976), Davis Canyon of current usage							
TTC	N33°43'50", W108°42'16"	212.0	23.0	26.7	29.7	0.72038	0.70912
Bull Basin ash							
G-55	N33°44'00", W108°56'07"	31.9	713.0	0.13	30.1	0.70787	0.70781
Andesite from Rain Creek (Ratté and Finnell, 1978)							
G-2	N33°10'53", W108°40'02"	132.0	418.0				
Datil Well Tuff (Stearns, 1962; Lopez, 1975; Osburn and Chapin, 1983)							
G-38	N33°58'59", W108°09'18"	213.0	258.0				
*T-409	N34°10'48", W107°55'48"	238.0	37.0	18.6	36.7	0.7162	0.70649
Tadpole Ridge Quartz Latite (Elston et al., 1973)							
*76T20	N32°53'22", W108°13'49"	164.0	160.0	3.0	31.9	0.7135	0.71216
Kneeling Nun Tuff (Jicha, 1954; Jones et al., 1967)							
*76T306	N32°45'39", W108°05'51"	143.0	343.0	1.2	34.4	0.7086	0.70801
**KNR-2		160.0	452.0	1.0	33.4	0.7087	0.70821
Fannee Rhyolite (Ferguson, 1927)							
TDW	N33°22'14", W108°42'26"	228.0	105.0	6.28	24.4	0.71025	0.70707
G-1	N33°06'25", W109°00'56"	233.0	399.0	1.69	26.0	0.71056	0.70993
Andesite from Eagle Peak (Rhodes, 1976)							
G-3	N33°43'54", W108°35'05"	49.8	565.0				
Sacaton Quartz Latite (Elston, 1968)							
G-11	N33°16'57", W108°43'57"	457.0	33.5	39.5	28.0	0.72352	0.70780

(continued on page 78)

Table 2 (continued)

Sample	Latitude, Longitude	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	K-Ar date (m.y.)	⁸⁷ Sr/ ⁸⁶ Sr _m	⁸⁷ Sr/ ⁸⁶ Sr _i
White ash from US-180 (Ratté and Finnell, 1978, Ratté, 1980)							
G-20	N33°35'35", W108°54'26"	40.5	924.0				
John Kerr Peak Quartz Latite (Rhodes and Smith, 1976, Marvin et al., 1987)							
G-43	N33°48'09", W108°28'11"	86.2	347.0	0.72	13.6	0.70656	0.70642
**JKP-1		130.0	382.0	1.0	13.6	0.7070	0.70681
Eagle Peak latite (Marvin et al., 1987)							
G-47	N33°40'27", W108°34'39"	66.1	395.0	0.48	26.0	0.70908	0.70890
Ash beds above Glenwood (Ratté and Finnell, 1978)							
G-76	N33°17'50", W108°54'08"	175.0	260.0				
Willow Creek dacite (Coney, 1976)							
G-81	N33°26'06", W108°35'22"	158.0	262.0	1.74	27.9	0.71018	0.70949
Nabours Mountain Quartz Latite (Rhodes, 1976)							
G-84	N33°17'02", W108°47'05"	282.0	58.0	14.1	28.4	0.71466	0.70899
Miscellaneous mafic and intermediate rocks							
Apache Creek basalt (Bikerman, 1976; Stinnett, 1980)							
G-4	N33°49'35", W108°37'15"	11.8	283.0	0.121	0.9	0.70363	0.70363
**AC-2		12.0	279	0.12	0.9	0.7034	0.7034
Basaltic andesite from Cox Canyon (Bikerman, 1976)							
G-5	N33°44'04", W108°28'35"	64.7	643.0	0.291	20.4	0.70776	0.70768
Basalt from Blue Range, (Ratté et al., 1969)							
G-22	N33°49'23", W109°01'20"	23.0	432.0				
" replicate		20.9	433.0				
Basalt from Pelona quadrangle (Stearns, 1962; Willard and Stearns, 1971)							
G-25	N33°57'43", W108°23'28"	150.0	719.0				
Basaltic andesite from Pelona quadrangle (Stearns, 1962; Willard and Stearns, 1971)							
G-27	N33°52'48", W108°19'13"	34.0	621.0				
Andesite from Mogollon quadrangle (Weber and Willard, 1959; Coney, 1976)							
G-28	N33°42'35", W108°54'28"	105.0	588.0				
Basalt from Mogollon quadrangle (Weber and Willard, 1959; Coney, 1976)							
G-30	N33°50'49", W108°58'16"	20.7	756.0				
Starkweather Canyon basalts (ascending sequence) (Ratté and Finnell, 1978)							
G-34A	N33°43'09", W108°47'16"	47.2	934.0	0.15	(25)	0.70665	(0.70660)
G-34B	N33°43'09", W108°47'16"	43.0	1021.0	0.12	(25)	0.70635	(0.70630)
G-34C	N33°43'09", W108°47'16"	55.3	856.0	0.19	(25)	0.70707	(0.70700)
Black phase latite from Pelona quadrangle (Stearns, 1962; Willard and Stearns, 1971)							
G-39B	N33°54'42", W108°16'31"	78.8	456.0				
San Francisco Box andesite							
G-40	N33°49'01", W108°46'52"	111.0	453.0	0.71	(25)	0.70994	(0.70968)
Basalt from Salvation Canyon (Willard and Stearns, 1971)							
G-42	N33°39'50", W108°20'36"	73.4	616				
" replicate		71.4	605				
Andesite of Hinkle Park (Ratté and Finnell, 1978)							
G-44	N33°37'56", W109°01'26"	58.6	850.0				
Grey andesite near Glenwood (Ratté and Finnell, 1978)							
G-75	N33°21'58", W108°55'02"	49.5	784.0				
Samples from the Alma 7 1/2' quadrangle (Houser, 1987)							
81-8	N33°29'00", W108°59'06"	111.0	464.0	0.69	(25)	0.70887	(0.70862)
81-12	N33°25'44", W108°58'34"	15.3	340.0	0.13	(25)	0.70615	(0.70610)
81-20	N33°24'40", W108°59'49"	11.5	416.0	0.08	(25)	0.70495	(0.70492)
81-23	N33°27'57", W108°54'38"	93.1	493.0	0.53	(25)	0.70873	(0.70854)

and the John Kerr Peak Quartz Latite for which the biotite date in Marvin et al. (1987) was used. The University of Pittsburgh K–Ar data was published in Marvin et al. (1987) except where noted. All Rb and Sr content and Sr isotopic analyses were performed in the isotope geology laboratory of Carleton University, Ottawa, Canada, except for the analyses (Bikerman, 1976) performed at the Scottish Universities Research and Reactor Centre (SID data in Tables 2 and 3).

Samples for XRF analysis were pulverized and pressed into boric acid powder in 32-mm planchettes using the techniques of Norrish and Chappell (1967) modified by John Blenkinsop (pers. comm. 1985), then analyzed for Rb and Sr on a Siemens XRF unit. Mass absorption calculations were made by comparison with the standard; precision checks were made by duplicate analysis of samples G–22, G–23 and G–42 (Table 2). A few samples were analyzed by isotope dilution mass spectrometry, and these results (Table 3), along with those from samples reanalyzed by XRF (Table 2), indicate that replicates agree within error limits of $\pm 5\%$ at the 2-sigma level. Values less than 10 ppm in XRF determinations should be considered as estimates.

The use of partial mineral separations is a modification of the conventional technique for collecting samples for Rb–Sr dating. In the standard method, suitably sized hand samples (usually 10 times the size of the larger crystals) are collected from sites in a single geological formation. The samples are selected for variety in mineral composition to show the widest range in Rb/Sr values. In the modification used here, very large samples collected for K–Ar dating were judged a mix of several hand samples. The physical differences in density and magnetic property used in the mineral-separation procedures were substituted for spatial differences in the field.

Isotopic analyses were performed on samples that had been dissolved and then passed through conventional ion exchange columns to separate strontium and rubidium. The mass spectrometer used was a Finnegan–MAT 261 multicollector. All strontium analyses were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$; the Eimer & Amend standard produced $^{87}\text{Sr}/^{86}\text{Sr} = 0.70802 \pm 0.00002$. Decay constants used were those of Steiger and Jäger (1977): $^{87}\text{Rb} = 1.42 \times 10^{-11} \text{ y}^{-1}$; $^{40}\text{K} = \text{beta}: 4.962 \times 10^{-10} \text{ y}^{-1}$; $\text{ec}: 0.581 \times 10^{-10} \text{ y}^{-1}$; and total: $5.543 \times 10^{-10} \text{ y}^{-1}$; $^{40}\text{K}/\text{K}_{\text{total}} = 1.167 \times 10^{-4}$.

Data

Data in Table 2 are divided into the Bloodgood Canyon Tuff, the Shelley Peak Tuff, felsic rocks that include the Davis Canyon Tuff, and mafic rocks that include all the basalts and andesites sampled in this study. Data from Stinnett (1980), Bornhorst and Brookins (1983), and Eggleston and Norman (1986) are included in this table. Dates and initial ratios shown in parentheses in the table are estimates.

TABLE 3—Isotope dilution results (in addition to XRF data from Table 2) used in calculating isochrons.

Sample	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{m}}$
Bloodgood Canyon Tuff G–7B (whole rock <100 mesh)	12.48	0.71475
G–7E (60–80 mesh, biotite and sanidine removed)	11.66	0.71482
G–23 (whole rock)	37.75	0.72463
Jerky Mountains Rhyolite G–6B (whole rock <100 mesh)	150.11	0.77084
Tuff breccia of Horse Springs G–31 (whole rock)	2.35	0.71087
G–31B (biotite)	30.69	0.72475
G–31E (partial separation)	0.995	0.71024

The age of the rock must be known to determine the $^{87}\text{Sr}/^{86}\text{Sr}$ in a rock at the time of its formation, the initial ratio, from the $^{87}\text{Sr}/^{86}\text{Sr}$ measured in the rock today; the radiogenically derived ^{87}Sr produced in the rock over that time is subtracted from the total present now to give the initial value. K–Ar ages published from the University of Pittsburgh determinations were used for this correction (Bikerman, 1972, 1976; Ratté et al., 1984; Marvin et al., 1987). The date of G–55 (Table 2) from the ash of Bull Basin is a new determination. This sample was collected from a 15-cm-thick white ash bed interbedded with crossbedded sandstones and conglomerates of the valley fill (?) Gila Formation. XRD analysis indicated the presence of clinoptilolite, montmorillonite, a Ca-zeolite, and some unknown material. The bed has 62.8 wt % SiO_2 , very low $\text{K}_2\text{O} + \text{Na}_2\text{O}$ (2.2%), and $\text{Rb/Sr} = 0.04$.

Results

The oldest ignimbrite sampled in this study is the Cooney Tuff associated with the Mogollon caldera (Ratté et al., 1984). This approximately 34-m.y.-old ash flow (G–8, G–9, Table 2) has an average Rb/Sr ratio of 2.5 ± 0.5 with an initial Sr ratio of 0.71082 ± 0.00025 for the two determinations.

The approximately 29-m.y.-old ignimbrites, possibly associated with the Gila Cliff Dwellings caldera, are the Davis Canyon and Shelley Peak Tuffs (Ratté et al. 1984). The Davis Canyon Tuff, older than the Shelley Peak Tuff, is lower in strontium content and in average initial Sr ratio (0.70891 ± 0.00077) than the Cooney Tuff. Sample TTC in Table 2 was collected by Rhodes as the lowest part of the type Tularosa Canyon Rhyolite (Rhodes and Smith, 1976), which in current usage includes both the Davis Canyon and the Vicks Peak Tuffs (Ratté, pers. comm. 1989). Here it is considered on stratigraphic grounds to be Davis Canyon Tuff. The Shelley Peak Tuff is higher in strontium (179 ppm average), lower in Rb/Sr, and slightly lower in initial Sr ratio (0.70860 ± 0.00041) than either the Davis Canyon or Cooney tuffs.

The Bloodgood Canyon Tuff associated with

the Bursum caldera is the most widespread unit in the area. This formation has low Sr content (38 ± 24 ppm average), Rb/Sr ratio of 7.14, and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio averaging 0.70948 ± 0.00035 for eight determinations, using the K–Ar date determined for each sample. If the 28.0 m.y. $^{40}\text{Ar}/^{39}\text{Ar}$ date of McIntosh (1989) is used for all the calculations of initial ratio in this unit, the average value changes slightly to 0.70928 ± 0.00036 , within error range. Combining the XRF determinations for the Rb/Sr values with isotope dilution determinations for partial separates (Table 3) allows the calculation of a Rb–Sr isochron (Fig. 2), using the method of York (1969), with an age of 26.7 ± 0.9 m.y. and an intercept (initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio) of 0.71008 ± 0.00021 . The initial ratio calculated from the isochron line is a little higher than that obtained by correcting the measured strontium ratios by K–Ar dates, reflecting the slightly lower Rb–Sr date. The mean square of weighted deviates (MSWD) for the isochron was 0.99, a number denoting good correlation or only instrumental rather than geological error (Brooks, 1966). Values of MSWD can be as high as the hundreds and values significantly greater than 1 are considered by Brooks (1966) as evidence of inhomogeneity of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the magma or of open-system behaviour of the whole-rock system. The calculated isochron value omits two of the partial separates (a quartz + sanidine mix and a biotite-rich mix) that are plotted above the line in Fig. 2. These samples acted as impure minerals rather than as whole rocks. The calculated date including these points is a meaningless 41.5 ± 1.3 m.y. with an intercept skewed to 0.7087 ± 0.0004 and MSWD of 45.

A Rb–Sr isochron on three samples from the Jerky Mountains Rhyolite yields a date of 28.9 ± 1.3 m.y., an intercept of 0.7096 ± 0.0006 , and a MSWD of 2.83 (Fig. 3; Tables 2 and 3). The MSWD slightly greater than unity is evidence for some geological input into the error. A sanidine separate from one of these rocks (square in Fig. 3) is plotted off the isochron line. The Rb–Sr isochron date is somewhat higher than the K–Ar dates for this rhyolite (Table 2). Using this Rb–Sr date instead of the K–Ar dates to calculate the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the two samples shown in Table 2 produces values of 0.71023 for G–6a and 0.70966 for ARS, identical within error to the intercept value. If the Rb–Sr date is correct, then the Jerky Mountains Rhyolite is older than previously reported (Bikerman, 1976; Marvin et al., 1987).

Four samples of the tuff breccia of Horse Springs provide a Rb–Sr isochron of 35.3 ± 1.6 m.y., intercept 0.70976 ± 0.00005 , and MSWD of 2.4, (Figure 4; Table 3). This date is similar to the K–Ar dates of 36.2 ± 2.0 m.y. date on 40–60-mesh biotite from sample G–31 and of 35.5 ± 2.2 m.y. of the USGS on biotite from that unit, (both in Marvin et al., 1987) and higher than the 32.2 m.y. date on 60–100-mesh biotite from G–31 (Table 2).

Mafic and intermediate-composition samples were analyzed for Rb and Sr contents,

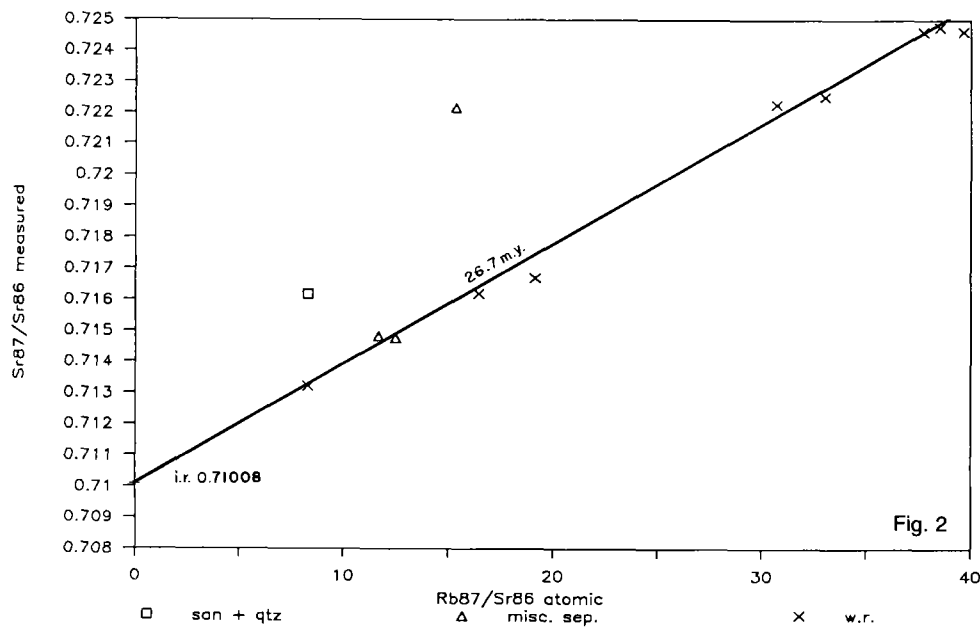


FIGURE 2—Rb-Sr isochron plot for the Bloodgood Canyon Tuff. Data from Tables 2 and 3. Abbreviations are: san, sanidine; qtz, quartz; misc. sep., miscellaneous partial mineral separation (see text); and w.r., whole-rock sample.

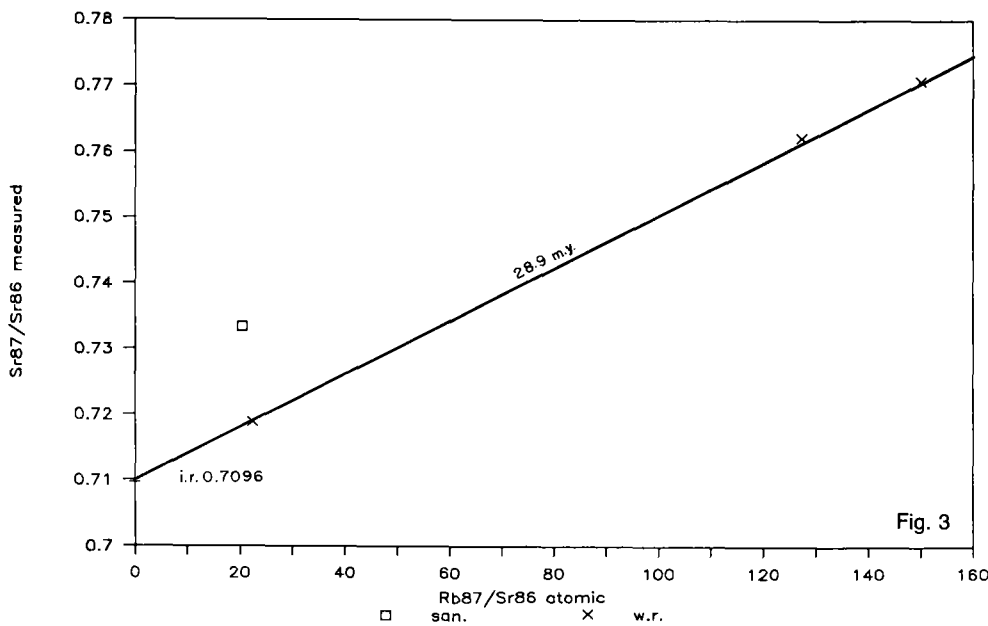


FIGURE 3—Rb-Sr isochron plot for the Jerky Mountains Rhyolite. Data from Tables 2 and 3; abbreviations from Figure 2.

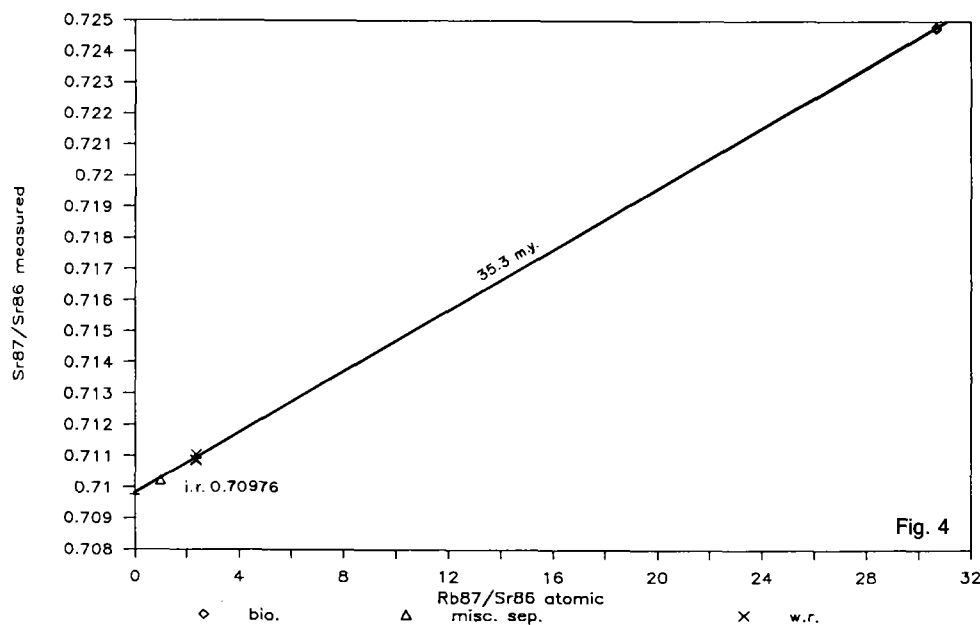


FIGURE 4—Rb-Sr isochron plot for the tuff breccia of Horse Springs. Data from Tables 2 and 3; abbreviations from Figure 2 and bio, biotite.

and sometimes isotopic Sr ratios (Table 2). The andesitic rocks analyzed had an average Rb content of 80.1 ppm (range 49.5 to 111 ppm), an average Sr content of 605 ppm (range 453 to 850), and Rb/Sr of 0.130 (range 0.063 to 0.245). Basaltic rocks had average Rb content of 44.1 ppm (range 11.5 to 150), average Sr content of 635.8 ppm (range 283 to 1021), and Rb/Sr 0.067 (range 0.027 to 0.209). Some overlap of the two groups occurs because the classifications used were based primarily on field names, and only secondarily on chemical analyses; only three of 11 basalts and four of eight andesites have been analysed for major elements. Mean initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for ten basalts and andesites combined was 0.70686 ± 0.00184 , with six basalts averaging 0.70575 ± 0.00127 and four andesites averaging 0.70861 ± 0.00086 .

Discussion

Twenty-two conventional K-Ar dates on sanidine in the Bloodgood Canyon Tuff (Ratté et al., 1984) average 26.9 ± 1.3 m.y., or essentially the same as the Rb-Sr date of 26.7 ± 0.9 m.y. (Fig. 2). Eliminating suspected incomplete fusions (McDowell, 1983; Marvin et al., 1987) by eliminating all dates younger than 25 m.y. gives a mean date of 27.3 ± 0.7 m.y. Biotites are less abundant than sanidines in the Bloodgood Canyon Tuff; eight K-Ar dates reported on biotite average 28.8 ± 1.4 m.y. The high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ determination on sanidine of McIntosh (1989) yielded 28.0 ± 0.03 m.y., slightly lower than the 28.3 ± 1.7 m.y. on the five biotites analyzed at the University of Pittsburgh. These factors suggest that conventional K-Ar dates on biotite are as accurate as high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ on sanidine but not as precise. The lower precision is a reflection of the higher atmospheric argon content of biotites. Conventional K-Ar dating of sanidines tends to produce somewhat lower values because of incomplete extraction of radiogenic argon, and these results should be regarded as minimums.

Reasons for variations in dates for a single formation include both geological and geochronological factors and especially selection criteria for discarding data. Geological criteria that affect K-Ar dates include: 1) argon loss by post-emplacement heating events; 2) argon loss during a long-term cooling his-

tory, a factor more important in plutons than volcanics; 3) retention of ambient argon from the magma chamber's atmosphere, argon which, if incorporated into minerals, leads to an older apparent age; 4) xenolithic argon; and 5) migration of potassium in or out of minerals during weathering or hydrothermal-fluid passage. This last factor is usually not a serious problem; experienced geochronologists usually collect unweathered material, and altered minerals normally are separated from unweathered ones during mineral separation. Experimental factors include: 1) incomplete fusions, hence incomplete argon extraction usually from sanidines, hence lowered ages; 2) high atmospheric argon that leads to large errors in the determination of radiogenic argon, a problem more prevalent with whole-rock samples than with minerals; and 3) possible inhomogeneity of samples. The last factor can lead to slight differences in the real values of potassium and argon in each aliquot analysed, with compositional or mineralogical variation; this factor is eliminated in $^{40}\text{Ar}/^{39}\text{Ar}$ dating that uses one aliquot per date. If all the other parameters are equal, then the long half-life of ^{87}Rb makes Rb-Sr dating less desirable for age determinations in the Cenozoic than either K-Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ dating. The high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ method and the multicollector Rb and Sr analyses have the lowest error caused by instrumental factors alone.

The different ages of the Jerky Mountains Rhyolite samples calculated by the Rb-Sr (28.9 m.y., Fig. 3) and K-Ar (26.2 m.y., 27.7 m.y., Table 2) methods may reflect incomplete fusion of the sanidines in argon analyses. If the K-Ar dates are correct, then the discrepancy in dates may be caused by a slight contamination of the magma chamber by radiogenic ^{87}Sr probably derived from the country rock. Alternatively, the older Rb-Sr date may reflect the residence time of the rhyolite in the magma chamber before eruption. K-Ar dates give the time of cooling of the erupted lava whereas Rb-Sr dates give the time of magma formation. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the intercepts for the Jerky Mountains Rhyolite (0.7096, Fig. 3) and the Bloodgood Canyon Tuff (0.71008, Fig. 2) are the same within experimental error; however, the Rb-Sr dates (28.9 m.y., 26.7 m.y.) barely overlap within error. Field relations in Y Canyon have been interpreted as Bloodgood Canyon Tuff merging into Jerky Mountains Rhyolite by the author but as the rhyolite overlying the tuff by others. The isotopic evidence is not conclusive. The potassium-rich (hence Rb-rich) phases in both the Bloodgood Canyon Tuff and the Jerky Mountains Rhyolite, shown in Figs. 2 and 3 plotted above their respective isochron lines, may reflect incorporation of excess ^{87}Sr in these early-forming phenocryst minerals. The excess ^{87}Sr could be derived from country-rock contamination of the magma.

Four samples of the tuff breccia of Horse Springs provide a Rb-Sr isochron of 35.3 ± 1.6 m.y., intercept of 0.70976 ± 0.00005 , and MSWD of 2.4 (Figure 4; Table 3). This date

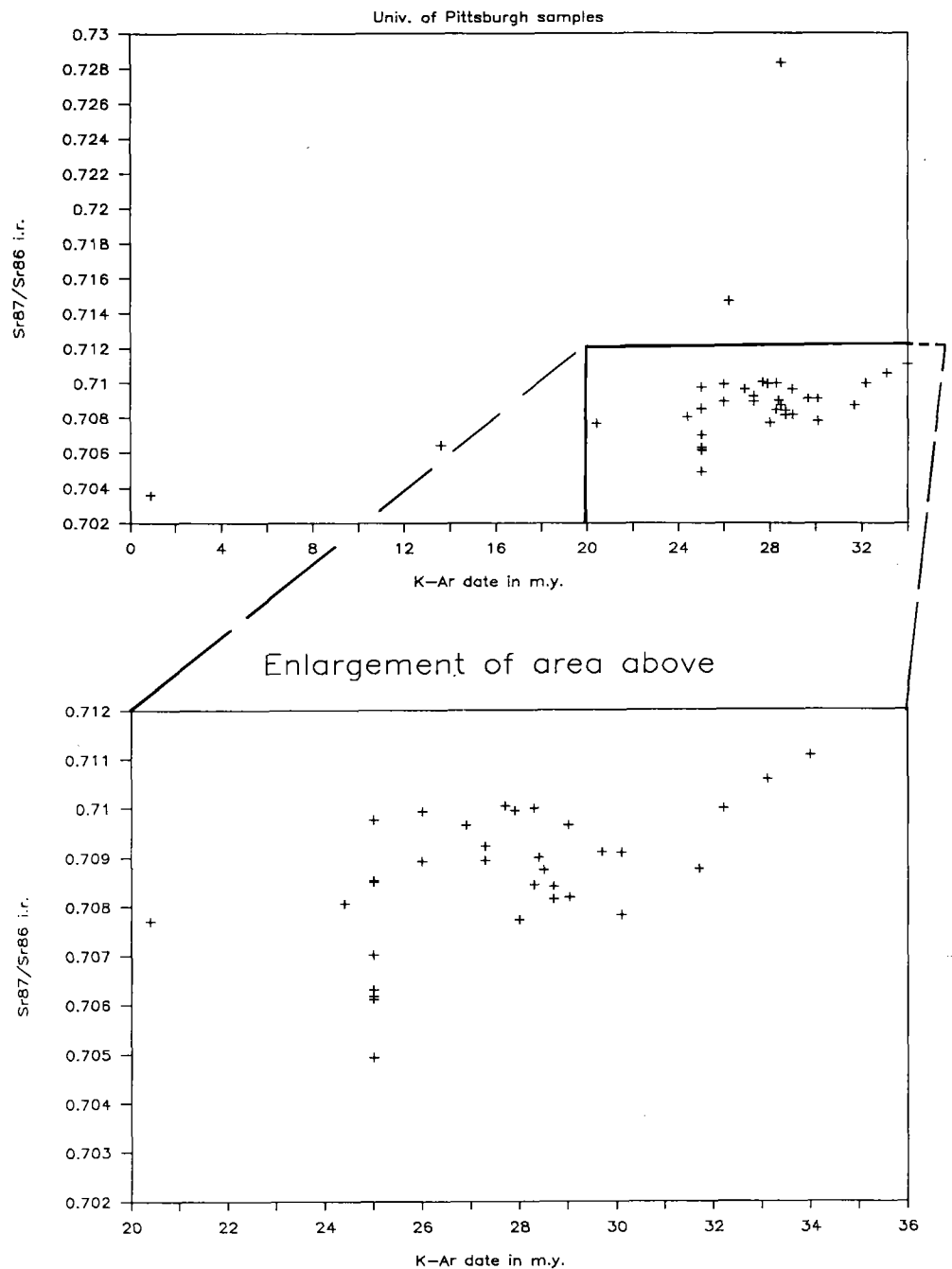


FIGURE 5—Variation of initial Sr ratio with age of sample. Data from Table 2. Inset shows the region of greatest concentration of data points. Note that concentration of points at 25 m.y. includes the samples with assigned dates.

is similar to the 36.2 ± 2.0 m.y. K-Ar date on 40–60-mesh biotite from sample G-31 (Marvin et al., 1987, p. 46, entry 123), similar to the 35.5 ± 2.2 m.y. K-Ar date of the USGS on biotite from that unit (Marvin et al., 1987, p. 45, entry 118), and higher than the 32.2 m.y. K-Ar date on 60–100-mesh biotite for sample G-31 listed in Table 2. The difference in apparent K-Ar dates for coarse- and fine-grained biotite in sample G-31 and also the difference between the Rb-Sr date and the K-Ar date of the fine-grained biotite may be a reflection of residence time of magma in the chamber. Fine-grained biotites may have formed later in the eruption cycle than coarse-grained biotites, would degas quicker and more completely on eruption, and would be

less likely to retain any extra argon. Another possibility is that the fine-grained biotite was a result of crushing and argon was lost during the separation process, although this is not considered likely. If the difference in dates is a geological phenomenon, the younger date would most closely reflect the actual eruption of the source of the ash flow, and the older dates the time of formation of the magma chamber. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for this formation is the same within error limit as that of the intercept value of the Bloodgood Canyon Tuff.

The John Kerr Peak Quartz Latite, whose K-Ar date of 13.6 m.y. (Marvin et al., 1987) was used for calculating initial Sr ratios of both samples in Table 2, has a slightly higher

initial Sr ratio than the Stinnett (1980) value (0.7067, Table 1B), which used a fission-track date of 21.4 m.y. The two ratio determinations agree reasonably well despite the rather large difference in the measured Rb contents. The John Kerr Peak Quartz Latite and the Datil Well Tuff (Table 2) are the only felsic rocks in the region with initial ratios lower than 0.707. The John Kerr Peak formation is a trachyandesite, which makes its lower initial Sr ratio less surprising. The other felsic rocks have an average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70989, which drops to 0.70899 if the three flow-banded rhyolite samples (ARS, G-6, G-46, Table 2) are omitted from the calculation. Initial Sr ratios of 0.708 to 0.709 found in felsic rocks usually are considered to be produced by mixing of mantle-derived magma with some crustal component, as in the San Juan Mountains volcanic field of southwestern Colorado (Lipman et al., 1978), in the Rio Grande rift (Perry et al., 1987), or in the Woods Mountains volcanic center of eastern California (Musselwhite et al., 1989). The initial Sr ratios of the younger felsic ash flows vary in the fourth decimal place and are within stated error limits. This similarity of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in ash flows of varied ages is suggestive of some commonality in the processes or rocks involved in their formation. These processes involve some degree of mixing of isotopically distinct end members, such as mantle-derived magma, continental crust, and various sedimentary units.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios decrease in younger samples (Figure 5) and regression analysis of the data gives a correlation coefficient of 0.71 when data from flow-banded rhyolites are omitted. This trend reflects the greater number of younger mafic-to-intermediate volcanic flows analyzed. The intermediate and mafic volcanic rocks have mean initial Sr ratios of 0.70861 ± 0.00086 for the andesites and 0.70429 for the two basalts. The Bearwallow Mountain Formation (now redefined as Bearwallow Mountain Andesite in Marvin et al., 1987) had initial ratios in the 0.7078 to 0.7083 range (Table 1B), which compare to 0.7077 for the Cox Canyon sample (G-5, Table 2) of Bikerman (1976), all within the range for andesites. Initial Sr ratios from approximately 0.707 to 0.709 are common in andesites and related rocks in the region (Bikerman, 1976; Stinnett and Stueber, 1976; Stinnett, 1980). These ratios may be evidence of interaction of mantle-derived magma, such as mid-oceanic ridge basalt (MORB) with an initial Sr ratio of 0.70292 (Allègre et al., 1986; Wasserburg, 1987), with continental crust having a mean value such as 0.7206, to produce volcanic rock isotopically similar to continental flood basalts (CFB), which have an average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70783 (Allègre et al., 1986). Country rock is not exposed in the immediate region, but, based on Pb isotope studies, Stacey and Hedlund (1983) suggest that Precambrian crust exists in the vicinity. This crust can be considered representative continental crust with a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.720599 (Allègre et al., 1986), or New Mexico rocks can be considered crust

TABLE 4—Summary of rubidium and strontium data for major ash flows: number of samples, average values and ranges for Rb/Sr, and average initial Sr ratios with errors listed in the last digits only.

Formation	Rb/Sr	$^{87}\text{Sr}/^{86}\text{Sr}_i$
Bloodgood Canyon Tuff (7)	7.14 (3.0–23.3)	0.70948 \pm 35
Shelley Peak Tuff (5)	1.04 (0.6–2.0)	0.70860 \pm 41
Davis Canyon Tuff (2)	4.41 (3.4–5.4)	0.70891 \pm 83
Cooney Tuff (2)	2.51 (2.0–3.1)	0.71082 \pm 26

suitable to produce the $^{87}\text{Sr}/^{86}\text{Sr}$ values found. These rocks include Precambrian granodiorites with ratio of 0.7249 ± 0.0034 and gneisses with 0.8163 ± 0.0899 (Brookins and Laughlin, 1973), or various Precambrian plutons of south-central New Mexico with values ranging from 0.71 to 0.79 (White, 1978). Some Paleozoic sedimentary rocks with $^{87}\text{Sr}/^{86}\text{Sr}$ values from 0.716 to 0.757 (Vuataz et al., 1988) or rocks with a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio similar in value to the 0.71523 average for sedimentary rocks (Allègre et al., 1986) may be present in sub-volcanic country rock.

For the Apache Creek basalt (G-4, AC-2, Table 2), the youngest basalt in the region, Bikerman (1976) reported a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.7036 and Stinnett (1980) reported 0.7034. The other true basalt analyzed (81–12, Table 2) is slightly higher in estimated initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, 0.70610. Other dark fine-grained rocks mapped as basalts are andesites or trachyandesites. The initial Sr ratios of the mafic rocks in this area can be compared to those of some basalts whose mean initial Sr ratios were calculated by Allègre et al. (1986). Specifically, the initial Sr ratio values of the ocean island basalts (OIB) (0.70405), the OIB + MORB mix (0.70359), or the oceanic basalts (OB) (0.70404) can be used to infer little or no interaction of the basaltic magma with country rock, as compared to CFB. Reid and Woods (1978) postulated that oceanic mantle underlies south-central New Mexico, and any of the oceanic basalt types listed above could be representative of that mantle.

Summary and conclusions

The Mogollon–Datil volcanic rocks are characterized by Sr isotopic differences that reflect parent magmas, country rock(s), and temporal and thermal evolution of the magma chamber(s). Parent magma(s) are most likely some type of mantle-derived basalt with a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the range 0.70263 (MORB from Atlantic and Pacific) to 0.70404 (OB), or even island arc basalts (IAB), which were produced in a subduction zone, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70497 (Allègre et al., 1986).

The felsic and intermediate volcanics all have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios well below those of the mean for continental crust or sediments and above those of all basalts discussed in Allègre et al. (1986). The only exceptions are the two samples of John Kerr Peak Quartz Latite and Datil Well Tuff (Bornhorst and Brookins, 1983) and an anoma-

lously low Bloodgood Canyon Tuff analysis (Bornhorst and Brookins, 1983) that are lower than the crustally contaminated CFB of Allègre et al. (1986). The Bull Basin ash with low Rb content has an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio identical to CFB. Currently, insufficient information exists to calculate the contributions of each of the potential end members to the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio measured in the rocks. However, an origin invoking mixing (and fractional crystallization of a mixture) of some kind of mantle-derived magma with country rock is supported by the isotopic data.

The chemical and mineralogical development within the magma chamber(s) prior to and during volcanism (i.e. Elston & Northrop, 1976; Ratté et al., 1984; Elston, 1984; McDowell, 1986; McIntosh et al., 1986) is suggested by: 1) the apparent age differences in a given ash flow using the Rb–Sr and K–Ar methods; 2) the different K–Ar dates on different minerals, or different size fractions of a given mineral, from the same rock; and 3) the variation in $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios within one ash flow. The last, along with the statistics (MSWDs higher than 1) from the isochrons, suggests that Sr isotopic equilibration may not have been totally achieved in the magma chamber. Lack of isotopic equilibration could have resulted from initial variation in country rock in contact with the magma or from inadequate mixing with viscous silicic magma.

Table 4 is a summary of the Rb/Sr values and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the major ash-flow tuffs. The Shelley Peak Tuff is quite distinct from the Bloodgood Canyon Tuff. The Davis Canyon Tuff has an intermediate Rb/Sr ratio, and an initial Sr ratio that overlaps the values in the two younger ash-flow tuffs.

The related flow-banded rhyolites, and other protrusive rhyolites, reflecting their generally low strontium values and high Rb/Sr ratios, have higher $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios than their coeval ash flows, and are not only more variable in initial Sr ratio but also much more sensitive to age correction in it.

The true basalts generally have $^{87}\text{Sr}/^{86}\text{Sr}$ values in a narrow range near 0.704, usually interpreted as direct derivation from a primary mantle source, while the andesites and basaltic andesites have higher and more variable values, suggesting some crustal involvement in their formation. The low Rb/Sr ratios usually make the age correction rather insignificant in Neogene or late Paleogene mafic rocks.

The use of partial mineral separations is a useful modification of conventional collection techniques when gathering data for a Rb–Sr isochron.

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Geographic Names

U.S. Board on Geographic Names

Lomitas Negras, Arroyo de las—watercourse, 8.9 km (5.5 mi) long, heads 2.4 km (1.5 mi) SE of Loma Duran at 35°18'36" N, 106°40'45" W, trends SE to disappear 6.4 km (4 mi) SW of Bernalillo; Sandoval County, NM; 35°15'55" N, 106°36'33" W; USGS map, Bernalillo 1:24,000; *not*: Arroyo de las Lomas Negras.

Tulloch Peak—peak, elevation 1,943 m (6,374 ft), 1.8 km (1.1 mi) NE of White Signal; Grant County, NM; sec. 13, T20S, R15W, NMPM; 32°34'07" N, 108°21'17" W; USGS map, White Signal 1:24,000; *not* Tullock Peak.

—David W. Love
NMBMMR Correspondent