

1-1997

Timing of Basaltic Volcanism along the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona, from $^{40}\text{Ar}/^{39}\text{Ar}$ Dates: Implications for Longevity of Cinder Cone Alignments

F. M. Conway
Southwest Research Institute

David A. Ferrill
Southwest Research Institute

Chris M. Hall
University of Michigan

Alan P. Morris
University of Texas at San Antonio

John A. Stamatakos
Southwest Research Institute

Follow this and additional works at: https://digitalcommons.usf.edu/geo_facpub

 [next page for additional authors](#)
Part of the [Earth Sciences Commons](#)

Scholar Commons Citation

Conway, F. M.; Ferrill, David A.; Hall, Chris M.; Morris, Alan P.; Stamatakos, John A.; Connor, Charles B.; Halliday, Alex N.; and Condit, Christopher, "Timing of Basaltic Volcanism along the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona, from $^{40}\text{Ar}/^{39}\text{Ar}$ Dates: Implications for Longevity of Cinder Cone Alignments" (1997). *School of Geosciences Faculty and Staff Publications*. 1663.
https://digitalcommons.usf.edu/geo_facpub/1663

This Article is brought to you for free and open access by the School of Geosciences at Digital Commons @ University of South Florida. It has been accepted for inclusion in School of Geosciences Faculty and Staff Publications by an authorized administrator of Digital Commons @ University of South Florida. For more information, please contact digitalcommons@usf.edu.

Authors

F. M. Conway, David A. Ferrill, Chris M. Hall, Alan P. Morris, John A. Stamatakos, Charles B. Connor, Alex N. Halliday, and Christopher Condit

Timing of basaltic volcanism along the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona, from $^{40}\text{Ar}/^{39}\text{Ar}$ dates: Implications for longevity of cinder cone alignments

F. Michael Conway,¹ David A. Ferrill,¹ Chris M. Hall,² Alan P. Morris,³ John A. Stamatakos,¹ Charles B. Connor,¹ Alex N. Halliday,² and Christopher Condit⁴

Abstract. Using high-precision stepwise-heating $^{40}\text{Ar}/^{39}\text{Ar}$ methods, we dated volcanic products of at least 12 vents cropping out along the northern segment of the Mesa Butte Fault in the San Francisco Volcanic Field, Arizona, where the relationship between fault and vent alignment is unambiguous. The $^{40}\text{Ar}/^{39}\text{Ar}$ isochron dates indicate that the Mesa Butte Fault hosted five episodes of volcanism over a 1 million year interval, from 1400 to 300 ka. The first episode occurred 1 km northwest of the trace of the Mesa Butte Fault, whereas the next two episodes were centered near the intersection of the Mesa Butte and Cedar Ranch faults. The final two episodes produced Red Mountain (750 ± 100 ka) and Shadow Mountain (300 ± 100 ka), respectively. Ages of vents representing the third (Mesa Butte) episode of volcanism (760 ± 50 ka to 900 ± 80 ka) indicate a systematic southwestward shift in the locus of volcanism along the Mesa Butte Fault that contrasts sharply with overall eastward younging of volcanism within the field. These data demonstrate that structures in basaltic volcanic fields are capable of hosting multiple episodes of volcanism over periods of time comparable to duration periods of composite volcanoes (10^6 years) but at significantly lower recurrence intervals. These results suggest that probability models of spatiotemporal recurrence of volcanism within basaltic volcanic fields should incorporate mapped structures, particularly where these structures have either hosted previous volcanic activity or are proximal to population centers or sensitive installations, such as nuclear power plants or waste repositories.

Introduction

Alignments of monogenetic vents are common and important features of areal basaltic volcanic fields. However, distinguishing alignments in volcanic fields comprising hundreds of vents is problematic because vents are often interspersed among a greater number of cones that are not obviously aligned [Draper *et al.*, 1994]. Recently, univariate and multivariate statistical methods have been used to identify vent alignments and improve the ability to discriminate these features objectively [e.g., Lutz, 1986; Wadge and Cross, 1988; Connor, 1990; Connor *et al.*, 1992]. Vent alignments delineated by statistical methods typically parallel regional and local structures, which suggests that volcanic alignments can form because ascending magmas exploit preexisting structures [Kear, 1964; Breed, 1964; Shoemaker *et al.*, 1978; Settle, 1979; Connor, 1990; Connor *et al.*, 1992].

In active Holocene volcanic fields, such as Craters of the Moon National Monument, Idaho [Kuntz *et al.*, 1986], or the Laki fissures, Iceland [Thordarson and Self, 1993], a strong

correlation has been recognized between structural trends (faults and fractures) and volcanic alignments consisting of contemporaneous cinder cones associated with single episodes of dike injection [Nakamura, 1977]. In older volcanic fields, however, this relationship is less certain because structures are obscured by basalt flows and tephra, and cinder cone ages are often poorly constrained. Thus, in older volcanic fields, volcanic alignments estimated by mathematical methods may include vents of significantly different ages [e.g., Connor *et al.*, 1992], each of which represents a discrete magmatic episode [Fedotov, 1981]. This model of alignment development assumes that faults and joints are capable of repeated capture of magma. To test the assumption, we dated basalts from 12 vents on the northern segment of the Mesa Butte Fault zone of the San Francisco Volcanic Field where the relationship between structure and vents is demonstrable. Our data complement existing sparse K/Ar ages [Damon *et al.*, 1974] and the well-established magnetostratigraphy [Tanaka *et al.*, 1991] and volcanic stratigraphy for the north central portion of the San Francisco Volcanic Field [Wolfe *et al.*, 1987a, b; Ulrich and Bailey, 1987; K. M. Mulaney, unpublished thesis, 1996]. The geochronology established here tracks the development of a cinder cone alignment along the Mesa Butte Fault through a series of temporally discrete eruptive events.

Recognition of the multiple nature of magma intrusion along the Mesa Butte Fault has important implications for volcanic hazard assessment in currently active volcanic fields, where faults on which volcanism has occurred may possibly impinge on population centers [e.g., Martin Del Pozzo, 1982;

¹Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, Texas.

²Department of Geological Sciences, University of Michigan, Ann Arbor.

³Department of Geology, University of Texas at San Antonio.

⁴Department of Geology, University of Massachusetts, Amherst.

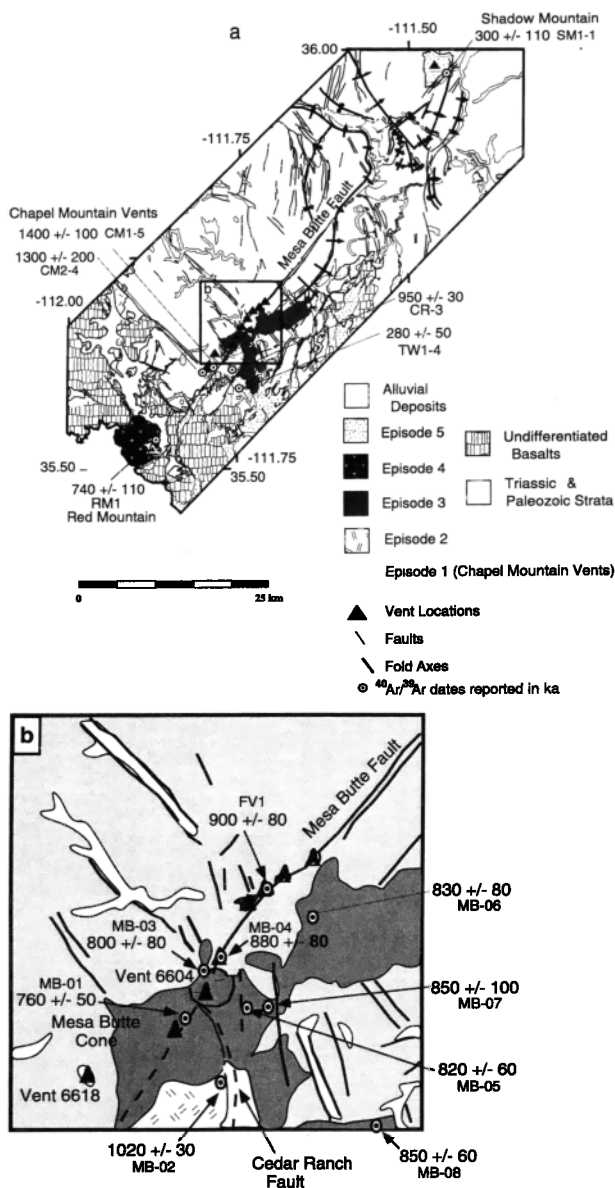


Figure 1. a. Geologic map of the Mesa Butte Fault zone of the north-central portion of the San Francisco Volcanic Field, northern Arizona illustrating locations of $^{40}\text{Ar}/^{39}\text{Ar}$ samples in this study (adapted from Ulrich and Bailey [1987] and Wolfe et al. [1987a]). (b) Enlarged geologic map illustrating sample locations in the vicinity of the Mesa Butte cone. (c) Inset map shows the field location. Also shown in the inset map are locations of Miocene volcanic centers, Tuba Butte and Wildcat Peak, that crop out along the northeast projection of the Mesa Butte Fault.

Seale, 1965] or sensitive installations, such as nuclear facilities [Lawrence Livermore National Laboratory, 1990; Smith et al., 1990; Connor and Hill, 1995]. For example, the proposed repository for high-level nuclear waste at Yucca Mountain, Nevada, is located within 20 km of several volcanic clusters that apparently erupted along north- and northeast-trending faults over the past 3.7 Ma [Crowe, 1990; Faulds et al., 1994]. Because it appears that faults in some volcanic fields are capable of episodic capture of magma over protracted periods of time, the trend, distribution, and volcanic history of faults that have

previously been intruded by magma may provide a physical basis for revision of probability studies of volcanic hazard.

Geologic History of the San Francisco Volcanic Field

The San Francisco Volcanic Field is one of several late Cenozoic, dominantly basaltic volcanic fields situated on the southern Colorado Plateau boundary (Figure 1). Lava flows and tephra of the 5000 km² volcanic field rest on an erosionally stripped surface of Permian and Triassic age sedimentary rock [Wolfe et al., 1987a, b; Ulrich and Bailey, 1987; Moore and Wolfe, 1987]. The onset of volcanism occurred about 6 Ma with the eruption of “rim basalts” on the western edge of the field [Luedke and Smith, 1978]. Since then about 600 cinder cones and 8 major silicic centers were emplaced in the San Francisco Volcanic Field. Volcanic activity has waned in the past 100 ka [Tanaka et al., 1986], and the emplacement of Sunset Crater in the eastern part of the field at about 1065 A.D. [Smiley, 1958] marks the field’s latest eruption.

Faults in the north central portion of the San Francisco Volcanic Field can be grouped into three populations that trend northwest, north, and northeast [Ulrich et al., 1984; Wolfe et al., 1987a, b; Ulrich and Bailey, 1987; Newhall et al., 1987; Holm, 1987] (Figure 1). In the west the field is bisected by the Mesa Butte Fault that extends discontinuously from Chino Valley, Arizona, northeast 150 km to Shadow Mountain [Shoemaker et al., 1978]. Additionally, the Mesa Butte Fault is colinear with a regional magnetic anomaly that continues at least 50 km farther northeast, suggesting the ancestral Mesa Butte Fault extends well beyond its presently mapped expression [Sauck and Sumner, 1971; Shoemaker et al., 1978]. In the San Francisco Volcanic Field the northern segment of the Mesa Butte Fault zone consists of the Mesa Butte and Cedar Ranch faults (Figure 1), each characterized by down-to-the-east motion. Regional structural relationships, especially contractional deformation along the northeast edge of the East Kaibab Monocline north of the field, suggests the Mesa Butte Fault has also experienced a component of right-lateral strike-slip motion. Timing of last motion on the Mesa Butte and Cedar

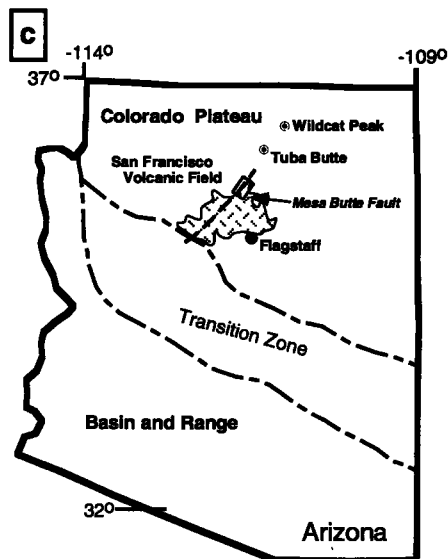


Figure 1. (continued)

Ranch faults varies across the volcanic field. In the north central part of the volcanic field, from the intersection of the Mesa Butte and Cedar Ranch faults southwestward, the two faults are mantled by late Tertiary to middle Quaternary volcanic rocks (Figure 1). To the northeast, lava flows of the late Quaternary Shadow Mountain volcanic center are displaced up to 13 m by a graben that lies on the projection of the Mesa Butte Fault [Condit, 1974].

Vent alignments are common in the San Francisco Volcanic Field and generally parallel local and regional structures [Breed, 1964; Shoemaker et al., 1978; Draper et al., 1994]. One of these alignments, comprising four cinder cones and five spatter vents, is colinear with the Mesa Butte Fault and extends 62 km along the base of the Mesa Butte fault line scarp. (For a more thorough geologic characterization of this area, see the 1:50,000 geologic maps of Ulrich and Bailey [1987] and Wolfe et al. [1987a, b].) Vents on the alignment include from southwest to northeast, Red Mountain, Mesa Butte cinder cone, Vent 6604, 5 fissure vents spaced 1–4 km north of Vent 6604, and Shadow Mountain, the northernmost vent of the San Francisco Volcanic Field (Figure 1). In addition to these nine vents, three cinder cones (Vents 6619 (Chapel Mountain), 6619a, and 6618) form a parallel alignment offset ≈ 1 km to the northwest of the Mesa Butte Fault (Figure 1). The three vents (informally referred to here as the Chapel Mountain vents) may be the surface manifestations of a dike(s) that was channeled at depth by the fault system before breaking vertically for the surface [after McDuffie et al., 1994].

Geochronology of the Mesa Butte Volcanic Alignment

Methods

Hand samples of 1–2 kg of fresh basalt were collected from 15 sites that include principal vents, lava flows of the Mesa Butte flow field, and two small-volume fissure vents located northeast of the Mesa Butte cone. The rocks were crushed and fragments of the 1–2-mm range were handpicked for analysis, carefully excluding fragments with obvious large phenocrysts. Neutron irradiation was done at the Phoenix-Ford Memorial Nuclear reactor at the University of Michigan. Analytical procedures follow closely those of Hall and Farrell [1995]. Typically, each sample consisted of four fragments, and each fragment was in turn step-heated during 30-s heating steps using a defocused beam of visible light from a Coherent Innova 5-W continuous argon ion laser operated in multiline mode. Mass discrimination was monitored daily by measuring the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of about 2.5×10^9 mL STP of atmospheric Ar. Fusion system blanks were subtracted from all sample gas fractions, and blanks were monitored frequently, typically every fifth sample fraction. The data were corrected for interference reactions due to Ca, K, and Cl, as well as for the decay of ^{37}Ar and ^{39}Ar . Potash contents and masses of individual samples are listed in Table 1, along with the total gas age. All ages were calculated assuming an age of 27.99 Ma for standard biotite FCT-3.

Results

Results of representative step-heating analyses are displayed as argon isotope correlation (isochron) diagrams (Figure 2), representative age-spectra diagrams, and reported as isochron dates (Table 2). Laser step-heating of small basalt chips can successfully separate argon from different mineral phases [Baski et al. [1991] and Ca/K plots in Figure 3) despite the

Table 1. Weight Percent K_2O , Total-Gas Age, and Mass Values Backcalculated From the K Content, $^{40}\text{Ar}/^{39}\text{Ar}$ age, and Measured Radiogenic ^{40}Ar Volume

Sample Number	K_2O wt %	TGA-1, ka	TGA-2, ka	Mass 1, mg	Mass 2, mg
MB-01	1.37	685	742	7.5	17.48
MB-02	1.06	952	898	5.9	1.69
MB-03	0.87	675	653	23.0	3.2
MB-03*	0.87	530	725	2.4	15.11
MB-04	1.0	579	678	3.1	4.7
MB-04*	1.0	812		12.6	
MB-05	1.12	668	757	6.4	15.7
MB-06	1.28	829	755	5.9	15.9
MB-07	0.91	732	683	8.3	5.0
MB-08	1.31	773	830	7.8	17.3
SM1-1	0.44	574	468	7.3	9.3
CM2-4	1.16	1600	1440	2.4	9.3
RM1	0.85	729	656	8.6	9.6
CR-3	1.93	969	1060	5.5	9.1
FV1	1.06	924	922	2.2	7.9
TW1-4	1.5	281	347	5.3	10.7
CM1-5	1.1	1510	1410	15.7	9.9

TGA-1 and TGA-2, and Mass 1 and Mass 2 are the total-gas ages (ka) and calculated mass values of specimens 1 and 2, respectively. The calculated mass is estimated to be accurate to about 20%. An asterisk indicates a replicate sample.

difficulty with nonuniform heating often associated with this technique. The method is also useful in separating radiogenic ^{40}Ar from initial ^{40}Ar , as demonstrated in Figure 2. The advantages of isochron dates over plateau or integrated total-gas dates are (1) there is no a priori assumption of initial argon composition, and (2) replicate isochron dates are readily combined, which increases data set size and thereby significantly improves the statistics. Additionally, the isochron dates, unlike the plateau (Figure 3) or integrated total-gas dates, are concordant with magnetic polarities reported for these rocks, which indicate a pre-Brunhes Age for most samples [Tanaka et al., 1991]. Moreover, age-spectra diagrams typically show a small but important systematic drop in age with a fraction of ^{39}Ar released, suggesting the presence of nonatmospheric initial Ar in some samples (Figure 3). In light of the possibility of excess Ar, argon isotope correlation diagrams offer the most reliable method to accommodate possible nonatmospheric initial ratios.

On $^{36}\text{Ar}/^{40}\text{Ar}$ versus $^{39}\text{Ar}/^{40}\text{Ar}$ isochron plots, sample analyses yielded robust linear arrays with mean squared weighted deviate values generally less than 2 (Figure 2). Apparent initial argon isotopic compositions are generally within error of the atmospheric value of 295.5. Some samples, however, show a trend toward slightly lower than atmospheric isotopic values (Table 2). Possible reasons for these lower than atmospheric values include minor nonargon contribution to mass 36, differential recoil of calcium-derived ^{36}Ar and ^{37}Ar , and ^{40}Ar loss at low-retentivity sites. The latter seems unlikely, however, because most of the low individual fraction ages are at the highest release temperatures. Alternatively, mass fractionation of Ar during incorporation into crystallizing lava flows has produced similarly low initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratios in some historic basalts and could be a contributing factor [Dalrymple, 1969].

Results indicate that the vents of the Mesa Butte alignment make up five groups based on age and distribution along the alignment. These groups are referred to here as the Chapel Mountain, Cedar Ranch, Mesa Butte, Red Mountain, and

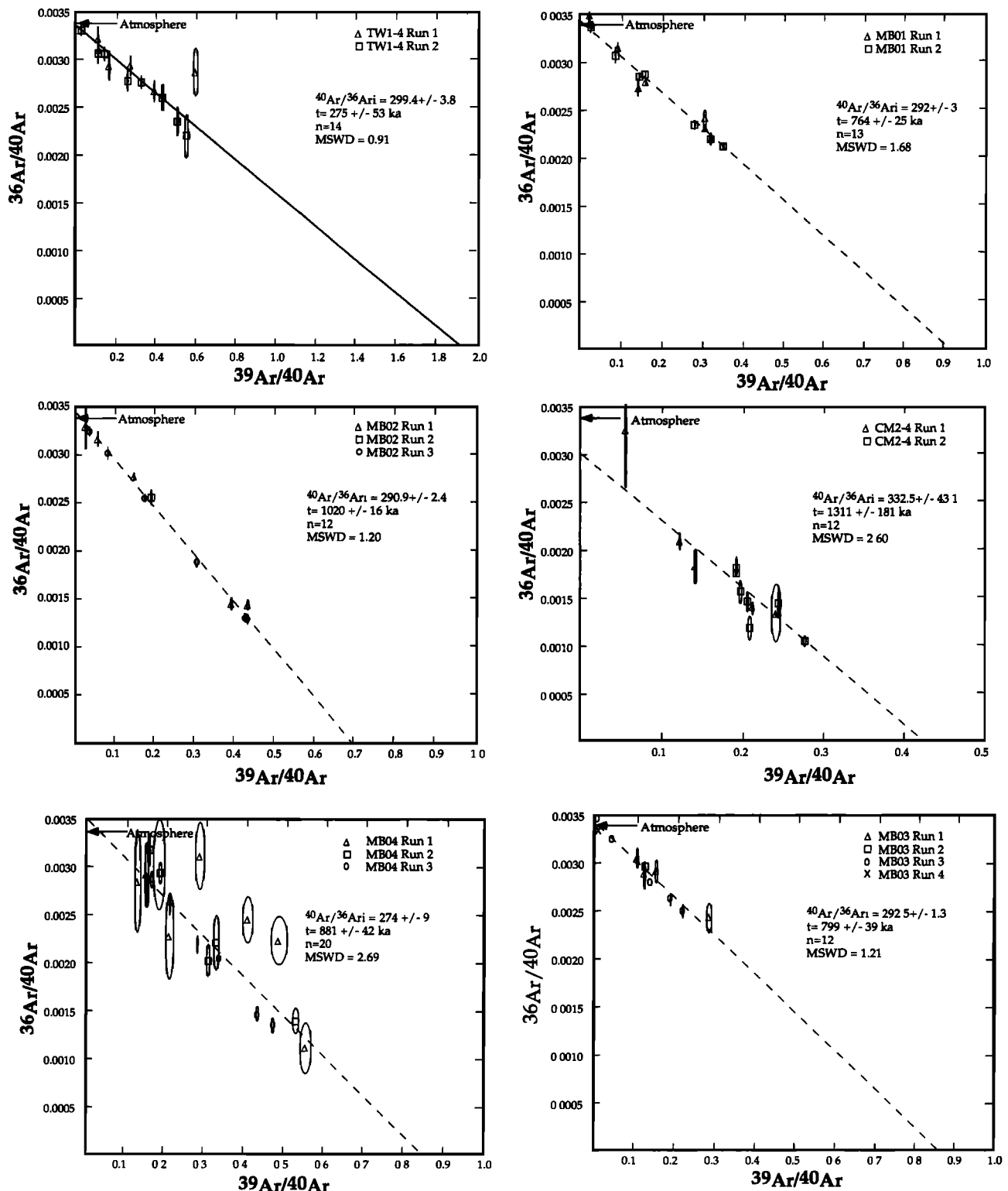


Figure 2. Isochron plots for $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock analysis of volcanics of the Mesa Butte vent alignment. Error ellipses are drawn at one sigma and all analyzed fractions are included. Note that the mean squared weighted deviate (MSWD) is generally less than 2, and the apparent initial argon isotopic composition is within error of the atmospheric ratio.

Shadow Mountain groups. The oldest group, Chapel Mountain, has an age of about 1300 ka and comprises the two dated Chapel Mountain vents (Table 2; Figure 4). A third Chapel Mountain vent, Vent 6618, consists of geochemically similar,

olivine-phyric basalt [Wolfe *et al.*, 1987b] which probably erupted at the same time.

The next oldest group, the Cedar Ranch group, consists of two lava flows (MB-2: 1020 ± 30 ka; CR-3: 950 ± 30 ka) in

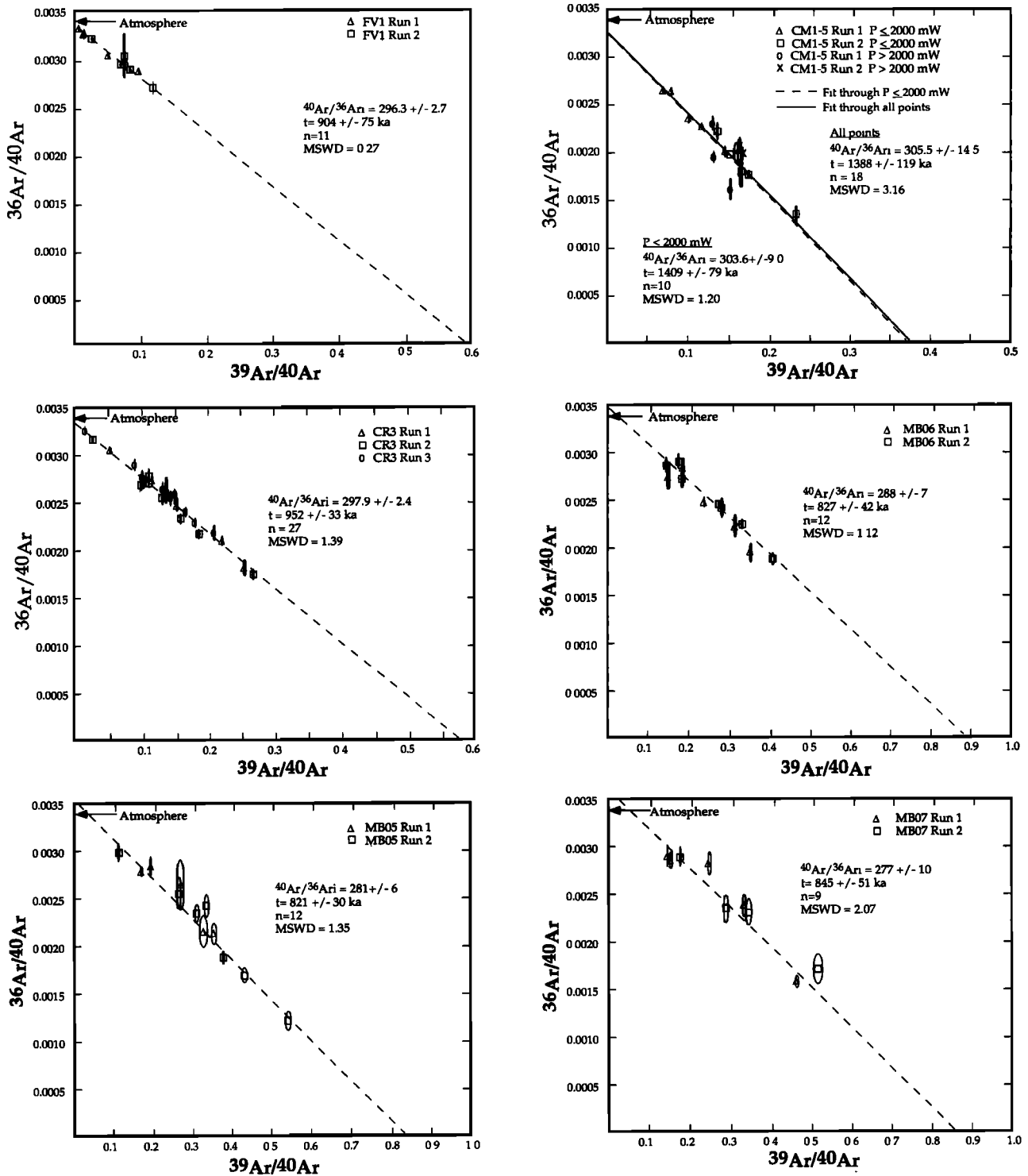


Figure 2. (continued)

stratigraphic contact that crop out on the Cedar Ranch fault line scarp, south of Mesa Butte cone (Figures 1 and 3). Isochron dates for the lava flows converge at about 1000 ka, and their 95% error bars nearly overlap (Table 2). The stratigraphically higher flow, MB-2, yields the older $^{40}\text{Ar}/^{39}\text{Ar}$ date that is supported by a previously published K-Ar date (1040 ± 40 ka) for that site [Damon et al., 1974] (Figure 2). Additionally, paleomagnetic analysis of block samples from MB-2, which involve thermal demagnetization experiments, confirm that the

lava flow is normally polarized. A normal magnetic direction is consistent with the age reported above and shows that the MB-2 flow erupted during the Jarimillo Normal-Polarity subchron (984–1049 ka; Cande and Kent [1992]). The stratigraphically lower lava flow, CR-3, is reversely magnetized [Tanaka et al., 1991] indicating a pre-Jaramillo emplacement age of more than 1049 ka (Figure 4). This is incongruent, however, with the $^{40}\text{Ar}/^{39}\text{Ar}$ date of 950 ± 30 ka reported above. The combined weight of the paleomagnetic and stratigraphic data and the

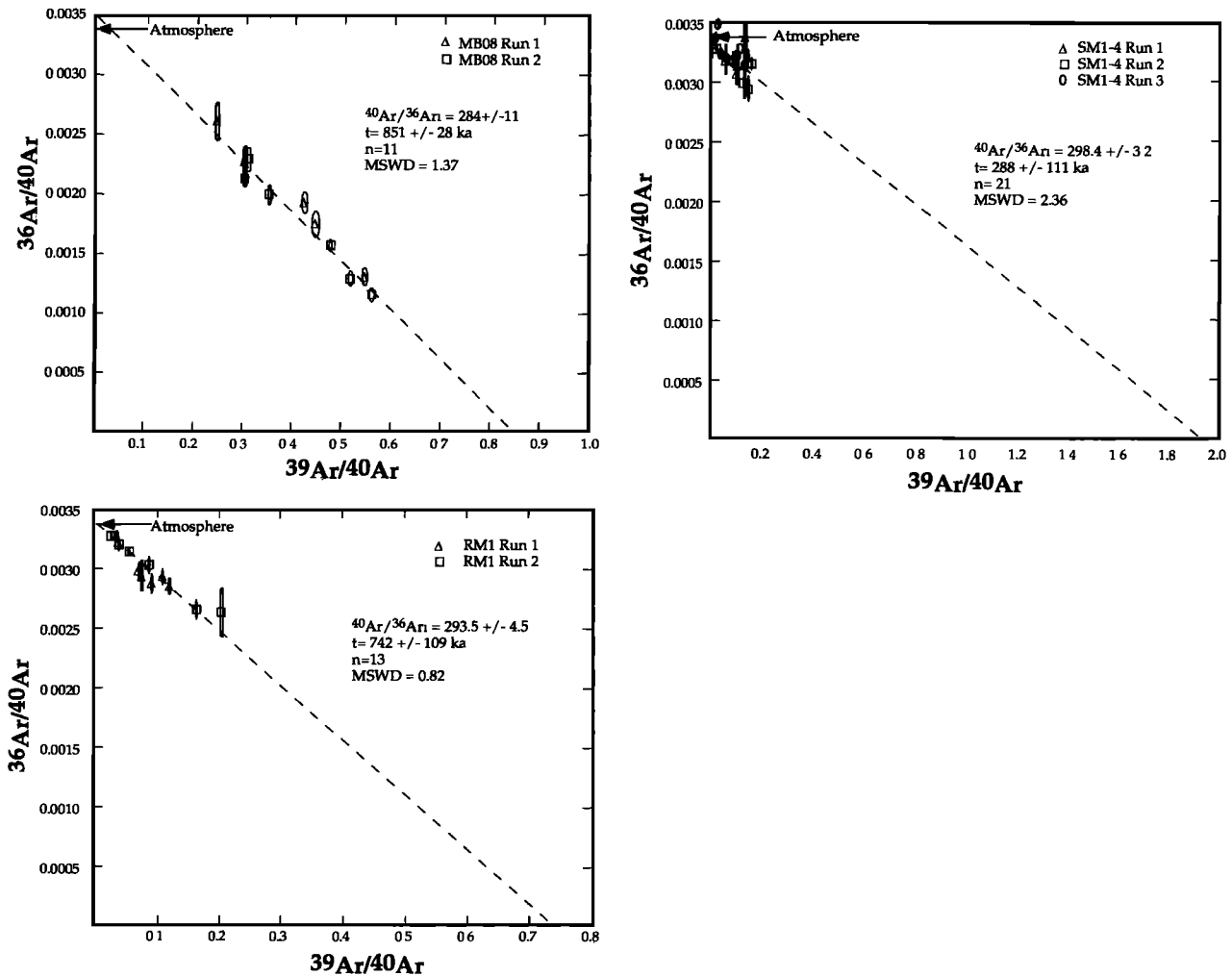


Figure 2. (continued)

good agreement of $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dates for the stratigraphically higher MB-2 lava flow require us to reject the 950 ± 30 age for the underlying CR-3 lava flow. The cause of error in this date is uncertain. Whole rock inductively coupled plasma analysis shows that the sample contains 1.93 wt % K_2O (Table 2), uncharacteristically high for a basalt with 52 wt % SiO_2 and 3.5% MgO [Ulrich and Bailey, 1987; Wolfe et al., 1987b], and suggests the possibility of postemplacement alteration.

On the basis of the proximity of the Cedar Ranch lava flows to the Mesa Butte cone and in the apparent absence of any other likely source, Ulrich and Bailey [1987] assigned the stratigraphically higher lava flow, MB-2, to the Mesa Butte cone. However, that assignment appears untenable based on the $^{40}\text{Ar}/^{39}\text{Ar}$ dates reported here, which indicate that the Mesa Butte cone is significantly younger than lava flows exposed along the Cedar Ranch fault scarp. We suggest that the vent(s) which produced MB-2 and CR-3 was buried by the younger eruptives of the Mesa Butte cone.

The Mesa Butte group is the largest and most widely dispersed and includes Mesa Butte cone (MB-01) and its associated lava flow field (MB-05, MB-06, MB-07, MB-08), Vent 6604 (MB-03), and the spatter vents north of Vent 6604 (Figure 1). Isochron dates of individual vents range from 900 ± 80 ka (FV-1) to 760 ± 50 ka (MB-01) but are generally indistinguishable at the 95% level of confidence (Table 2). Mesa Butte

cone (MB-01; 760 ± 50 ka) and Vent 6604 (MB-03; 800 ± 80 ka) are reversely magnetized which further constrains their emplacement age to older than 780 ka [Cande and Kent, 1992]. Damon et al. [1974] reported K-Ar dates for sites MB-4 and MB-6. Their date for MB-4 (830 ± 40 ka) is similar to the new date reported here (Figure 4), whereas the K-Ar age for site MB-6 (1380 ± 160 ka) is significantly older and is incongruent with the volcanic stratigraphy [Ulrich and Bailey, 1987] and thus is rejected.

There appears to be a correlation between vent age and distance along the Mesa Butte alignment for the four dated vents of the Mesa Butte group (Figure 5). Apparently, the first vent to erupt in this group was one of the northeasternmost spatter vents (FV-1), which erupted about 900 ka (Table 2). The other dated vents of the Mesa Butte group including spatter vent (MB-4), Vent 6604 (MB-03), and Mesa Butte cone (MB-1) young sequentially to the southwest, indicating the locus of volcanism migrated southwestward during this episode of activity.

The Red Mountain vent and its associated lava flow field are located 17 km southwest of Mesa Butte cone on the southwest projection of the Mesa Butte Fault (Figure 1). A lava flow from Red Mountain (RM-1) gave a $^{40}\text{Ar}/^{39}\text{Ar}$ isochron date of 740 ± 110 ka (Table 2). This is similar to the date reported for the Mesa Butte cone, but Red Mountain basalts are normally

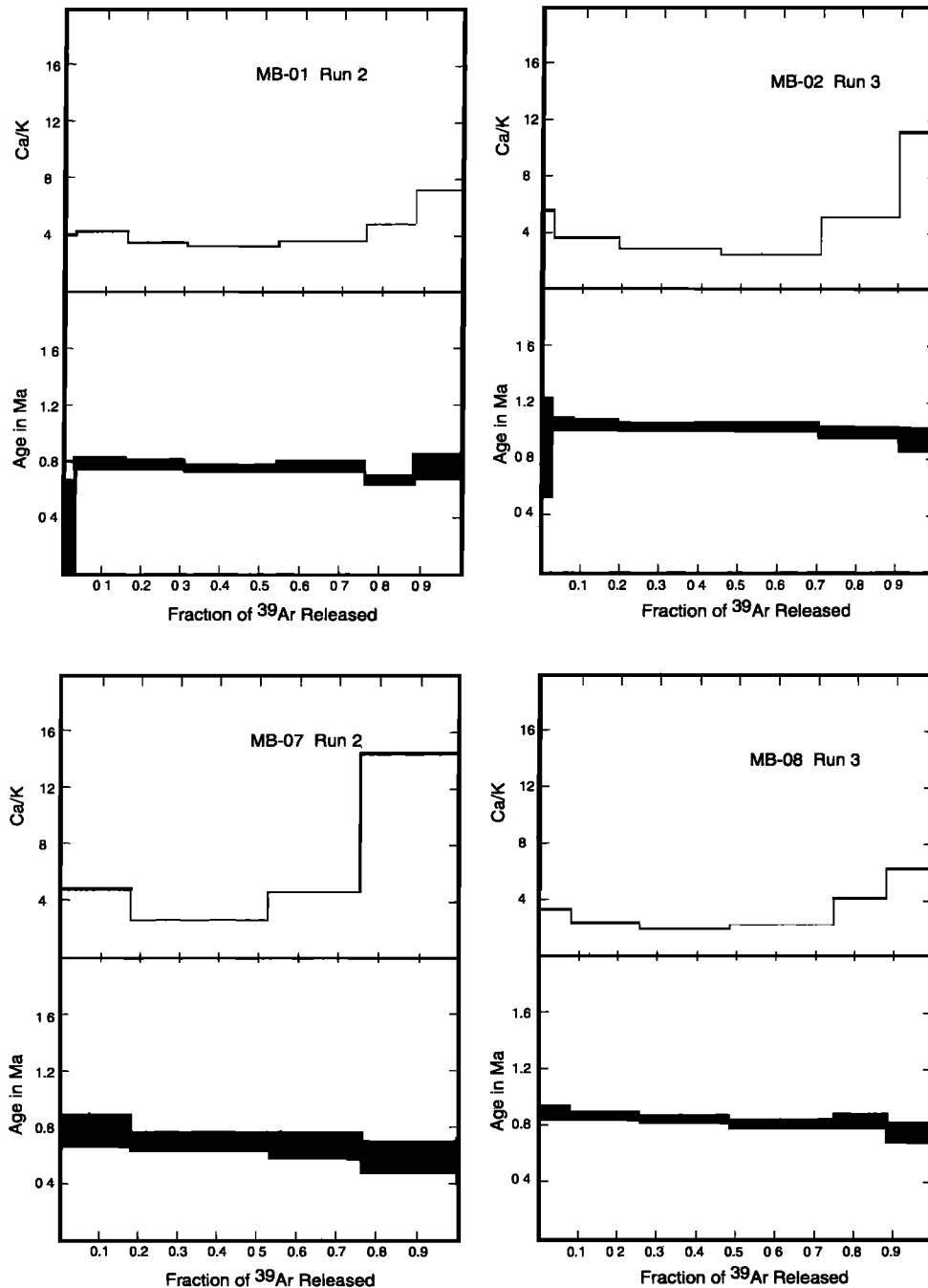


Figure 3. The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and corresponding Ca/K for representative samples from along the Mesa Butte vent alignment. All error boxes are ± 1 sigma.

polarized, indicating that emplacement occurred during the Brunhes epoch (after 780 ka) [Tanaka *et al.*, 1991].

Nearly 400 kyr elapsed between the activity at Red Mountain and onset of volcanic activity at Shadow Mountain, the northeasternmost vent on the Mesa Butte alignment (Figure 1). The Shadow Mountain complex includes a cinder cone, several boccas, and a surrounding lava flow field and is located about 30 km northeast of Mesa Butte cone [Condit, 1974; Ulrich *et al.*, 1984]. A basalt flow erupted at Shadow Mountain (SM1-1), yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ isochron date of 300 ± 110 ka (Table 2). This date is significantly younger than a K-Ar date of 620 ± 230 ka reported by Damon *et al.* [1974] (Figure 4). More

importantly, a date of 300 ± 110 ka for Shadow Mountain demonstrates that episodic volcanism on the Mesa Butte alignment recurred through most of the Quaternary.

Discussion

Basaltic volcanism occurred along the studied segment of the Mesa Butte Fault zone between about 1400 and 300 ka, resulting in a volcanic alignment of 12 vents that extend 60 km. Thus small-volume basaltic volcanism occurred along the Mesa Butte Fault over an interval of time comparable to the duration of formation of individual composite volcanoes [e.g.,

Table 2. The $^{40}\text{Ar}/^{39}\text{Ar}$ Stepwise-Heating Isochron Results For Vents and Lava Flows Erupted on the Mesa Butte Fault Zone

E#	Sample Number	Location	(n) # Points	MSWD	$^{40}\text{Ar}/^{36}\text{Ar}$	Age, ka
<i>Shadow Mountain</i>						
1	SM1-1	111.48°W 35.98°N	21	2.36	298.4 ± 3.2	300 ± 110
	TW1-4	111.73°W 35.59°N	14	0.91	299.4 ± 3.8	280 ± 50
<i>Red Mountain</i>						
2	RM1	111.87°W 35.52°N	13	0.82	293.5 ± 4.5	740 ± 110
<i>Mesa Butte</i>						
3	MB-01	111.75°W 35.65°N	13	1.68	292 ± 6	760 ± 50
	MB-03	111.75°W 35.66°N	12	1.21	292.5 ± 2.6	800 ± 80
	MB-05	111.74°W 35.65°N	12	1.35	281 ± 12	820 ± 60
	MB-06	111.72°W 35.68°N	12	1.12	288 ± 14	830 ± 80
	MB-07	111.73°W 35.65°N	9	2.07	277 ± 20	850 ± 100
	MB-04	111.74°W 35.67°N	20	2.69	274 ± 18	880 ± 80
	MB-08	111.70°W 35.63°N	11	1.37	284 ± 22	850 ± 60
	FV1	111.73°W 35.68°N	11	0.27	296.3 ± 2.7	900 ± 80
<i>Cedar Ranch</i>						
4	CR-3	111.75°W 35.61°N	27	1.39	297.9 ± 2.4	950 ± 30
	MB-02	111.74°W 35.63°N	12	1.20	290.4 ± 4.8	1020 ± 30
<i>Chapel Mountain</i>						
5	CM2-4	111.80°W 35.61°N	12	2.60	332.5 ± 43.1	1300 ± 200
	CM1-5	111.79°W 35.62°N	18	3.16	305.5 ± 14.5	1400 ± 100

E# is the episode number discussed in the text. MSWD is the mean squared weighted deviate and a measure of the linearity of the isochron line. All errors are reported at 2 sigma.

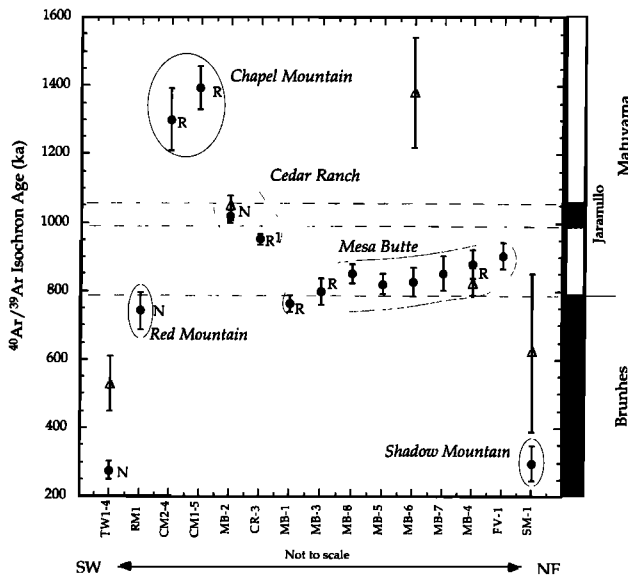


Figure 4. The $^{40}\text{Ar}/^{39}\text{Ar}$ isochron ages of vents and lava flows of the Mesa Butte Fault zone. Solid circles represent $^{40}\text{Ar}/^{39}\text{Ar}$ isochron ages. Triangles are K-Ar ages determined by Damon *et al.* [1974]. Error bars represent one standard error. Boundary between the Brunhes and Matuyama polarity chronons and the limits of the Jaramillo polarity subchron are from Cande and Kent [1992]. R indicates the unit is reversely magnetized, while N indicates a normal polarity [after Tanaka *et al.*, 1991]. Superscript 1 indicates a $^{40}\text{Ar}/^{39}\text{Ar}$ age which is incongruent with volcanic stratigraphy and paleomagnetic data; the dashed ellipse about the Cedar Ranch episode indicates uncertainty in the data as described in the text.

Crisp, 1984], encompassing nearly one sixth the history of the San Francisco Volcanic Field. Recurrence on the alignment, however, was considerably less than that of composite volcanoes, and the total volume output of the alignment ($<5 \text{ km}^3$) is only a fraction of that of the San Francisco Peak composite volcano (121 km^3) located in the central part of the field [Holm, 1986].

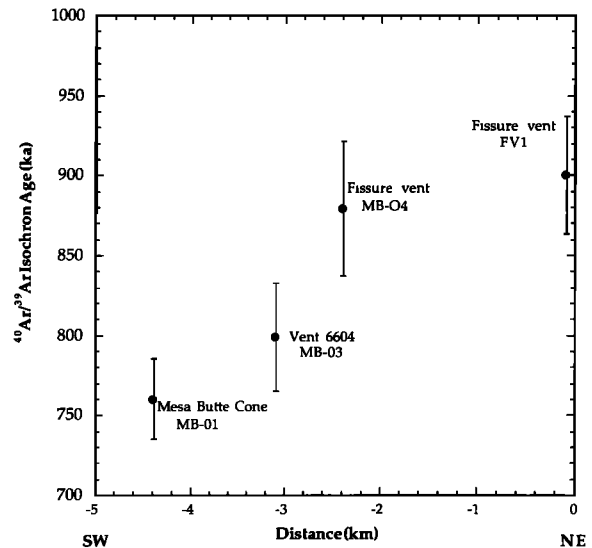


Figure 5. The $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age versus distance, from southwest to northeast, along the Mesa Butte Fault for vents erupted during the Mesa Butte episode.

The combination of very low recurrence rates, duration of volcanic activity along the alignment, and geochemical heterogeneity of basalts erupted along the alignment [Wolfe *et al.*, 1987a; Ulrich and Bailey, 1987; F. M. Conway *et al.*, unpublished data, 1996] is consistent with the idea that vents are the products of discrete magma batches that were captured in the shallow subsurface (<10 km) by the fault system. High precision $^{40}\text{Ar}/^{39}\text{Ar}$ isochron dates indicate that volcanism was episodic rather than continuous, with five discrete episodes of vent formation. Volcanism on the alignment began with the emplacement of the Chapel Mountain vents about 1300 ka. At about 1000 ka the locus of volcanism migrated to the Mesa Butte Fault trace near the intersection of the Mesa Butte and Cedar Ranch faults. This area remained a locus of episodic volcanism until the end of the Matuyama Epoch (780 ka), suggesting the intersection of these faults was significantly easier to dilate than were other portions of the Mesa Butte fault system.

From 900 to 780 ka the locus of volcanism apparently systematically migrated southwestward about 5 km from spatter vents north of Vent 6604 to the Mesa Butte cone. This short-duration pattern of southwestward younging contrasts with long-term eastward migration of volcanism, at ≈ 2.1 cm/yr, prevalent in the San Francisco Volcanic Field since about 2 Ma [Tanaka *et al.*, 1986]. Considering that the lateral distance of magma migration along the alignment was small (≈ 4.5 km) compared to its vertical rise through the crust (≈ 40 km; Warren [1969]), southwestward migration may reflect the response of rising magma to local perturbations in the stress field, fault geometry, or differences in material strength along the Mesa Butte Fault, perhaps related to earlier intrusions along the fault. By about 750 ka the locus of volcanism moved 17 km farther southwest to the site of Red Mountain. The period from about 740 to 300 ka was a time of apparent repose along the Mesa Butte alignment. At about 300 ka the locus of volcanism moved 65 km northeast to Shadow Mountain; meanwhile, Vent 4536, located off the southwest projection of the Cedar Ranch Fault (about 7.5 km southeast of Red Mountain) but on the projection of a narrow graben that parallels the Mesa Butte Fault zone, erupted the Tappan Wash lava flow (Table 2), suggesting that magma was still rising along the southwest part of the fault system. Clearly, the spatial distribution of vents along the alignment shows no correlation with overall eastward shifts in volcanic activity in the field as a whole [Tanaka *et al.*, 1986].

Although this paper focuses on basaltic volcanism of the northern segment of the Mesa Butte Fault, there is considerable evidence that silicic volcanism of the southwestern San Francisco Volcanic Field was largely controlled by the southern segment of the Mesa Butte Fault system. The major silicic composite volcanoes of Bill Williams Mountain (4.2–3.6 Ma), Sitgreaves Mountain (2.9–1.9 Ma), Kendrick Peak (2.7–1.4 Ma), and Slate Mountain (1.5 Ma) all lie on the southwest projection of either the Mesa Butte or Cedar Ranch faults [Shoemaker *et al.*, 1978; Tanaka *et al.*, 1986; Newhall *et al.*, 1987; Wolfe *et al.*, 1987b]. In addition, two isolated Miocene volcanic centers, Tuba Butte and Wildcat Peak, crop out on the northeastern projection of the Mesa Butte Fault, 35 and 55 km northeast of Shadow Mountain, respectively (Figure 1). The two centers are located on a regional magnetic anomaly that Shoemaker *et al.* [1978] linked to displacement in the Precambrian basement rock along the ancestral Mesa Butte Fault. Although the precise ages of the vents are unknown, we infer from their presence that the Mesa Butte Fault zone influenced

magma ascent and vent emplacement on the southwestern Colorado Plateau throughout the Neogene.

Implications

The northern segment of the Mesa Butte Fault zone repeatedly served as a pathway for magma ascent for at least 1 m.y. Isochron dates reported here indicate that volcanism along the northern Mesa Butte Fault was episodic, and successive episodes were separated in time by as much as 400 k.y. Additionally, spatial patterns of volcanism along the Mesa Butte alignment were apparently independent of field-wide trends, evinced by the large lateral shifts in volcanic loci between successive episodes. These observations help clarify trends observed in the development of young, potentially active volcanic alignments. For example, the largely Holocene Craters of the Moon Volcanic Field shows similar eruption patterns characterized by multiple episodes of magmatism and frequently shifting loci of volcanism along the Great Rift [Kuntz *et al.*, 1986], albeit on a timescale of thousands of years. On an even shorter timescale a shift in the locus of eruption during the Great Tolbachik Fissure Eruption (1975–1976) diverted activity from the Northern Breakout 10 km south to South Cone in just 3 days [Fedotov and Markhikhin, 1983]. This behavior contrasts sharply with eruption patterns of other short-lived fissure eruptions, such as the Laki fissure eruption [Thordarson and Self, 1993] where vent-spacing is of the order of tens or hundreds of meters, vent migration is typically unidirectional, and vents young in the direction of dike propagation. Observations of episodic volcanism along the Mesa Butte Fault indicate that probability models for the recurrence rate of basaltic volcanism within volcanic fields [Ho, 1991; Crowe and Perry, 1989; Connor and Hill, 1995] may be significantly improved by explicitly including mapped structures in estimates of spatio-temporal recurrence rates because independent magmatic episodes may recur along structures even following periods of quiescence lasting 100 ka or more.

Acknowledgments. This work was performed at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under contract number NRC-02-93-005. Additional funding was provided by the NRC Office of Research (NRC 04-92-082). The work was initiated as part of the Tectonic Processes in the Central Basin and Range research project and continued on behalf of the Office of Nuclear Material Safety and Safeguards. This paper is an independent product of CNWRA and does not necessarily reflect the views or regulatory position of the NRC. We acknowledge the assistance of the Phoenix-Ford Memorial Reactor and argon isotopic analyses benefitted from the assistance of Marcus Johnson and Eleanor Dixon. We thank Richard Klar and Peggy Hunka for assistance in preparing the geologic map of the Mesa Butte Fault zone and Ron Martin for providing technical assistance. Editorial review by B. Long and technical reviews by G. Stirewalt, B. Hill, and B. Sagar are gratefully acknowledged. Critical reviews by E. Wolfe (USGS), K. Foland (Ohio State University), and T. Onstott (Princeton University) greatly improved this manuscript.

References

- Baksi, A. K., C. M. Hall, and D. York, Laser probe $^{40}\text{Ar}/^{39}\text{Ar}$ dating studies on submilligram whole-rock basalt samples: The age of the Steen's Mountain geomagnetic polarity transition (revisited), *Earth Planet. Sci. Lett.*, 104, 292–298, 1991.
- Breed, W. J., Morphology and lineation of cinder cones in the San Francisco Volcanic Field, in *Contributions to the Geology of Northern Arizona*, *Bull. Mus. North. Ariz.*, 40, 65–71, 1964.
- Cande, S. C., and D. V. Kent, A new geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, 97, 13,917–13,951, 1992.
- Condit, C. D., The geology of Shadow Mountain, in *Geology of North-*

- ern Arizona With Notes on the Archeology and Paleoclimate, Part 1, *Regional Studies*, Rocky Mtn. Sec. Meet. Flagstaff, Ariz., Guideb., edited by T. N. Karlstrom, G. A. Swann, and R. L. Eastwood, pp. 454–463, Geol. Soc. Am., Boulder, Colo., 1974.
- Connor, C. B., Cinder cone clustering in the TransMexican volcanic belt: Implications for structural and petrologic models, *J. Geophys. Res.*, *95*, 19,395–19,405, 1990.
- Connor, C. B., and B. E. Hill, Three nonhomogeneous Poisson models for the probability of basaltic volcanism: Application to the Yucca Mountain region, Nevada, *J. Geophys. Res.*, *100*, 10,107–10,125, 1995.
- Connor, C. B., C. D. Condit, L. S. Crumpler, and J. C. Aubele, Evidence of regional structural controls on vent distribution: Springerville Volcanic Field, Arizona, *J. Geophys. Res.*, *97*, 12,349–12,359, 1992.
- Crisp, J. A., Rates of magma emplacement and volcanic output, *J. Volcanol. Geotherm. Res.*, *20*, 177–211, 1984.
- Crowe, B. M., Basaltic volcanic episodes of the Yucca Mountain Region, paper presented at International Topical Meeting on High-Level Radioactive Waste Management, Am. Nucl. Soc., La Grange Park, Ill., 1990.
- Crowe, B. M., and F. Perry, Volcanic probability calculations for the Yucca Mountain site: Estimation of volcanic rates, paper presented at *Nuclear Waste Isolation in the Unsaturated Zone, Focus '89*, pp. 326–334, Am. Nucl. Soc., La Grange Park, Ill., 1989.
- Dalrymple, G. B., $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of historic lava flows, *Earth Planet. Sci. Lett.*, *6*, 47–55, 1969.
- Damon, P. E., M. Shafiqullah, and J. S. Leventhal, K-Ar chronology for the San Francisco Volcanic Field and rate of erosion of the Little Colorado River, in *Geology of Northern Arizona With Notes on the Archeology and Paleoclimate, Part 1, Regional Studies*, Rocky Mtn. Sec. Meet., Flagstaff, Ariz., Guideb., edited by T. N. Karlstrom, G. A. Swann, and R. L. Eastwood, pp. 221–235, Geol. Soc. of Am., Boulder, Colo., 1974.
- Draper, G., Z. Chen, F. M. Conway, C. B. Connor, and C. Condit, Structural control of magma pathways in the upper crust: Insights from the San Francisco Volcanic Field, Arizona, *Geol. Soc. Am. Abstr. Programs*, *26(7)* A115, 1994.
- Faulds, J. E., J. W. Bell, D. L. Feuerbach, and A. R. Ramelli, Geologic map of the Crater Flat area, Nevada, *Nev. Bur. Mines Geol. Map*, *101*, 1994.
- Fedotov, S. A., Magma rates in feeding conduits of different volcanic centres, *J. Volcanol. Geotherm. Res.*, *9*, 379–394, 1981.
- Fedotov, S. A., and Ye. K. Markhinin, *The Great Tolbachik Fissure Eruption: Geological and Geophysical Data 1975–1976*, Cambridge Earth Sci. Ser., 341 pp., Cambridge Univ. Press, New York, 1983.
- Hall, C. M., and J. W. Farrell, Laser $^{40}\text{Ar}/^{39}\text{Ar}$ ages of tephra from Indian Ocean deep-sea sediments: Tie points for the astronomical and geomagnetic polarity timescales, *Earth Planet. Sci. Lett.*, *133*, 327–338, 1995.
- Ho, C.-H., Time trend analysis of basaltic volcanism at the Yucca Mountain site, *J. Volcanol. Geotherm. Res.*, *46*, 61–72, 1991.
- Holm, R. F., Field guide to the geology of the central San Francisco Volcanic Field, northern Arizona, in *Geology of Central and Northern Arizona*, Rocky Mtn. Sec., edited by J. D. Nations, C. M. Conway, and G. A. Swann, pp. 27–41, Geol. Soc. Am., Boulder, Colo., 1986.
- Holm, R. F., Geomorphic evidence for youngest dated faults in north-central Arizona, *Mt. Geol.*, *24*, 19–25, 1987.
- Kear, D., Volcanic alignments north and west of New Zealand's central volcanic region, *N Z J. Geol. Geophys.*, *7*, 24–44, 1964.
- Kuntz, M. A., D. E. Champion, E. C. Spiker, and R. H. Lefebvre, Contrasting magma types and steady state volume-predictable basaltic volcanism along the Great Rift, Idaho, *Geol. Soc. Am. Bull.*, *97*, 579–594, 1986.
- Lawrence Livermore National Laboratory, Assessment of potential volcanic hazards for the new production reactor site at the Idaho Rep. UCLRL-ID-104722, 98 pp., Natl. Eng. Lab., Volcanism Working Group, Lawrence Livermore Natl. Lab., Livermore, Calif., 1990.
- Luedke, R. G., and R. L. Smith, Map showing distribution, composition, and age of the late Cenozoic volcanic centers in Arizona and New Mexico, *U.S. Geol. Surv. Map*, *I-1091-A*, 1978.
- Lutz, T. M., An analysis of the orientation of large scale crustal structures: A statistical approach based on areal distributions of pointlike features, *J. Geophys. Res.*, *91*, 421–434, 1986.
- Martin Del Pozzo, A. L., Monogenetic volcanism in Sierra Chichinautzin, Mexico, *Bull. Volcanol.*, *45-1*, 9–24, 1982.
- McDuffie, S. M., C. B. Connor, and K. D. Mahrer, A simple 2-D stress model of dike-fracture interaction, *Eos Trans. AGU*, *75(16)*, Spring Meet. Suppl., 345, 1994.
- Moore, R. B., and E. W. Wolfe, Geologic map of the east part of the San Francisco Volcanic Field, north-central Arizona, scale 1:50,000, *U.S. Geol. Surv. Misc. Field Stud. Map*, *MF-1960*, 1987.
- Mulaney, K. M., The petrology and geochemistry of lavas from cinder cones along alignments in the SP region of the San Francisco Volcanic Field, Arizona, M.S. thesis, 169 pp., Univ. of Mass., Amherst, 1996.
- Nakamura, K., Volcanoes as possible indicators of tectonic stress orientation—Principle and proposal, *J. Volcanol. Geotherm. Res.*, *2*, 1–16, 1977.
- Newhall, C. G., G. E. Ulrich, and E. W. Wolfe, Geologic map of the southwest part of the San Francisco Volcanic Field, north-central Arizona, scale 1:50,000, *U.S. Geol. Surv. Misc. Field Stud. Map*, *MF-1958*, 1987.
- Sauck, W. A., and J. S. Sumner, Residual aeromagnetic map of Arizona, Univ. of Ariz., Tucson, 1971.
- Seale, E. J., Auckland volcanic district, New Zealand Volcanology (Northland, Coromandel, and Auckland), in *New Zealand Geological Survey Handbook*, Inf. Ser., vol. 49, edited by B. N. Thompson and L. O. Kermode, pp. 90–101, Dep. of Sci. and Ind. Res., New Zealand, 1965.
- Settle, M., The structure and emplacement of cinder cone fields, *Am. J. Sci.*, *279*, 1089–1107, 1979.
- Shoemaker, E. M., R. L. Squires, and M. J. Abrams, Bright Angel and Mesa Butte Fault systems of northern Arizona, in *Cenozoic Tectonics and Regional Geophysics of the Western Cordillera*, edited by R. B. Smith, and G. P. Eaton, *Mem. Geol. Soc. Am.*, *152*, 341–368, 1978.
- Smiley, T. L., The geology and dating of Sunset Crater, Flagstaff, AZ, *Field Conf. Guideb. N. M. Geol. Soc.*, *9th*, Socorro, N. M., pp. 186–190, 1958.
- Smith, E. I., T. R. Feuerbach, and J. E. Faulds, The area of most recent volcanism near Yucca Mountain, Nevada: Implications for volcanic risk assessment, in *Proceedings of International Topical Meeting on High-Level Radioactive Waste Management*, vol. 1, pp. 81–90, Am. Nucl. Soc., La Grange Park, Ill., 1990.
- Tanaka, K. L., E. M. Shoemaker, G. E. Ulrich, and E. W. Wolfe, Migration of volcanism in the San Francisco Volcanic Field, Arizona, *Geol. Soc. Am. Bull.*, *97*, 129–141, 1986.
- Tanaka, K. L., T. C. Onstott, and E. M. Shoemaker, Magnetostratigraphy of the San Francisco Volcanic Field, Arizona, *U.S. Geol. Surv. Bull.*, *1929*, 35 pp., 1991.
- Thordarson, Th., and S. Self, The Laki (Skaftár Fires) and Grímsvotn eruptions in 1783–1785, *Bull. Volcanol.*, *55*, 233–263, 1993.
- Ulrich, G. E., and N. G. Bailey, Geologic map of the SP Mountain part of the San Francisco Volcanic Field, north-central Arizona, scale 1:50,000, *U.S. Geol. Surv. Misc. Field Stud. Map*, *MF-1956*, 1987.
- Ulrich, G. E., G. H. Billingsley, R. Hereford, E. W. Wolfe, L. D. Nealey, and R. L. Sutton, Map showing geology, structure, and uranium deposits of the Flagstaff $1^\circ \times 2^\circ$ quadrangle, Arizona, scale 1:250,000, *U.S. Geol. Surv. Map*, *I-1446*, 1984.
- Wadge, G., and A. Cross, Quantitative methods for detecting aligned points: An application to volcanic vents in the Michoacán-Guanajuato volcanic field, Mexico, *Geology*, *16*, 815–818, 1988.
- Warren, D. H., A seismic-refraction survey of crustal structure in central Arizona, *Geol. Soc. Am. Bull.*, *80*, 257–282, 1969.
- Wolfe, E. W., G. E. Ulrich, and C. G. Newhall, Geologic map of the northwest part of the San Francisco Volcanic Field, north-central Arizona, scale 1:50,000, *U.S. Geol. Surv. Misc. Field Stud. Map*, *MF-1957*, 1987a.
- Wolfe, E. W., G. E. Ulrich, R. F. Holm, R. B. Moore, and C. G. Newhall, Geologic map of the central part of the San Francisco Volcanic Field, north-central Arizona, scale 1:50,000, *U.S. Geol. Surv. Misc. Field Stud. Map*, *MF-1959*, 1987b.
- C. Condit, Department of Geology, University of Massachusetts, Amherst, MA 01003. (e-mail: c.condit@geolgeog.umass.edu)
- C. B. Connor, F. M. Conway, D. A. Ferrill, and J. A. Stamatakos, Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, TX 78238. (e-mail: cconnor@swri.edu; mconway@swri.edu; dferrill@swri.edu; jstam@swri.edu)
- C. M. Hall and A. N. Halliday, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109. (e-mail: chris.m.hall@um.cc.umich.edu; alex.halliday@um.cc.umich.edu)
- A. P. Morris, Department of Geology, University of Texas at San Antonio, San Antonio, TX 78249.

(Received May 3, 1996; revised September 12, 1996; accepted September 17, 1996.)