Migration of volcanism in the San Francisco volcanic field, Arizona

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ABSTRACT

The remanent magnetization of volcanic rocks has been determined at 650 sites in the San Francisco volcanic field in the southern part of the Colorado Plateau. The polarity of remanent magnetization—combined with K-Ar age determinations, spatial and petrographic associations, stratigraphic relations, and state of preservation of the cinder cones—provides a basis for assignment to known magnetic polarity epochs of 610 mafic vents and >100 intermediate to silicic flows, flow sequences, and vents. The age assignments for basaltic rocks include 243 Brunhes (<0.73 Ma) vents, 220 Matuyama (0.73 to 2.48 Ma) vents, and 147 pre-Matuyama (2.48 to about 5.0 Ma) vents. Basaltic volcanism migrated northeastward before Matuyama time at a rate of ~1.2 cm/yr and eastward (S87° ± 5°E) over the past 2.5 m.y. at a rate of 2.9 ± 0.3 cm/yr. Concomitant acceleration in total magma production (from 75 to 1,400 × 10^{-6} km^3/yr) and frequency of basaltic eruptions (from 1 per 17,000 yr to 1 per 3,000 yr) occurred between 5 and 0.25 Ma. For the past 0.25 m.y., magma production (~180 × 10^{-6} km^3/yr) and perhaps eruption frequency have decreased. This evolutionary sequence, coupled with the lead and strontium-isotopic composition of the rocks, can be explained by magmatism caused by shear heating at the base of the lithosphere. We propose that this eastward drift of volcanic activity represents absolute westward motion of the North American plate. Our model is in agreement with a model in which the African plate is fixed to the deep mantle.

INTRODUCTION

Previous geologic investigations of the San Francisco volcanic field (Robinson, 1913; Colton, 1936; Cooley, 1962; Moore and others, 1976) established that its youngest rocks are located in its eastern part. Determination of K-Ar ages for silicic centers and some basalts (Damon and others, 1974; McKee and others, 1974) led to recognition of northeastward migration of volcanism along the Mesa Butte fault system (Ulrich and Nealey, 1976) and eastward migration in the eastern part of the field (Smith and Luedke, 1984).

In order to determine the stratigraphy of the volcanic rocks and to study the migration of volcanism in detail, we began a systematic paleomagnetic investigation in the summer of 1977. We determined directions of thermoremanent magnetization for >560 sites, adding to the ~90 sites already analyzed by other workers. The broad magnetostratigraphy of the volcanic field was worked out by combining paleomagnetic results, field relations determined from detailed geologic mapping, and K-Ar ages obtained by other workers. Assignment of virtually all of the rocks of the volcanic field to broad age classes enabled us to examine (1) the pattern of eruption loci and volume of volcanic material erupted as a function of time, (2) the migration of volcanism in this field compared with that of other volcanic fields in the western United States, (3) a possible model for deep-seated magma generation, and (4) implications for absolute motion of the North American plate.

GEOLOGIC SETTING

The San Francisco volcanic field in northern Arizona is one of several dominantly basaltic volcanic fields of late Cenozoic age on the southern Colorado Plateau (Fig. 1). The field extends somewhat more than 100 km east-west and ~70 km north-south (Fig. 2). It includes >600 basaltic volcanoes of Tertiary (Pliocene) and Quaternary age and associated lava flows and pyroclastic deposits that cover ~4,800 km^2. They rest on Miocene volcanic rocks and erosional surfaces of low relief cut on Permian and Triassic sedimentary rocks (Wolfe and others, 1983). Post-Miocene basaltic volcanism was broadly contemporaneous with the silicic and intermediate volcanism that formed Bill Williams Mountain, Sitgreaves Mountain, Kendrick Peak, San Francisco Mountain, O'Leary Peak, and isolated domes (Fig. 2).

An extensive Miocene–early Pliocene volcanic field, composed of rocks informally referred to as the "rim basalts," borders the San Francisco field on the south. This field makes up part of the Mogollon Rim that forms the southern margin of the Colorado Plateau. Its rocks were more extensively affected by Cenozoic normal faulting and are much more dissected than are the lavas of the San Francisco field. Most published K-Ar ages of the rim basalts lie in the range of 5 to 8 m.y. (Luedke and Smith, 1978). They are overlapped along their northern margin by rocks of the San Francisco volcanic field. The oldest volcanoes and lava flows of the San Francisco field also occur in this area, and it is not clear if there was a break in time between rim-basalt volcanism and volcanism of the San Francisco field. The southwest boundary of the field is hence ill defined and has been arbitrarily drawn.

Late Cenozoic activity along the regional fault systems (Fig. 2) caused normal offset of the rocks that underlie the San Francisco volcanic rocks and also locally of the volcanic rocks themselves. These fault systems are related to large, ancient systems of faults that cut the Proterozoic crystalline basement (Shoemaker and others, 1978). Several silicic volcanic centers, including Bill Williams, Sitgreaves, and Kendrick, are situated along or near the Mesa Butte system. The Oak Creek Canyon fault system trends north to underlie the San Francisco Mountain stratocone. Along its extent south of San Francisco Mountain, there are several 2- to 1-m.y.-old vents that produced benmoreite, dacite, and rhyolite. The Doney fault, which may be a northern extension of the Oak Creek Canyon fault system, underlies O'Leary Peak. Faults in the Mesa Butte and Oak Creek Canyon systems offset volcanic rocks that are 6 to 1 m.y.

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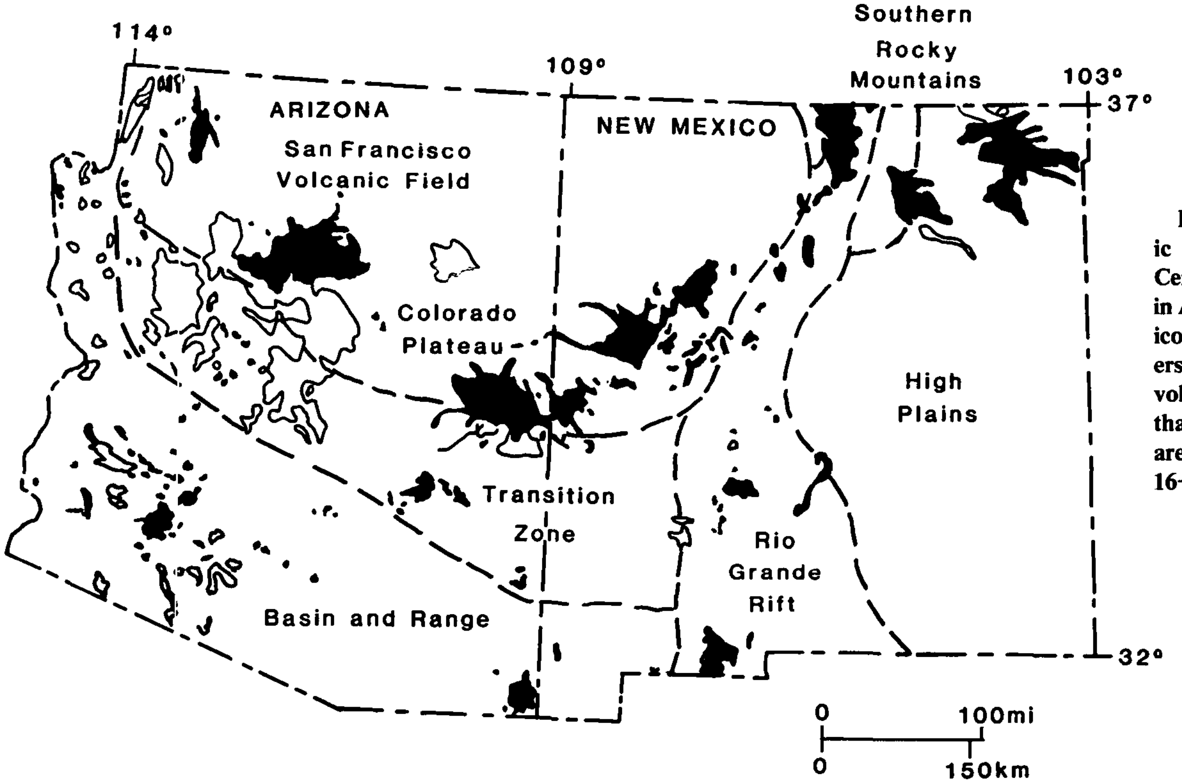

Figure 1. Physiographic provinces and late Cenozoic volcanic fields in Arizona and New Mexico (from Wolfe and others, 1983). Dark areas, volcanic rocks younger than 5 m.y.; outlined areas, volcanic rocks 5 to 16+ m.y.

old. Faults of the smaller Cataract Creek system (not shown in Fig. 2) trend northwest across the western part of the volcanic field. The Mesa Butte and other minor faults of various trends cut the rim basalts. Many basaltic cinder cones, as well as silicic volcanoes, are aligned along exposed faults or follow the trend of faults in each system.

PALEOMAGNETIC SAMPLING AND LABORATORY METHODS

At the 535 sample sites of mafic vents and lava flows analyzed in this study, 440 separate eruptions related to mapped cinder cones are represented. In some cases, deposits from a single eruption or eruptive episode were sampled at two or more sites. Vent locations of ~34 sampled lava flows and 1 basaltic tuff bed are unknown, because either the vents or the proximal parts of the flows are buried; other similar flows were not sampled. A few buried vents probably exist in the San Francisco field that are not represented in this study; however, their omission should not materially affect our conclusions. The sampled sites include nearly all of the vents or their associated flows, or both, west of the longitude of O'Leary Peak. A total of 115 sites was sampled at intermediate to silicic centers and isolated domes and flows, including a succession of andesite and dacite flows on San Francisco Mountain (T. C. Onstott, unpub. data). East and north of San Francisco Mountain, paleomagnetic studies were carried out by Babbitt (1963), Champion (1980 and 1983, written commun.), J. N. Kellogg (unpub. data), and T. C. Onstott (unpub. data). The total of 650 sample sites analyzed in this study includes 90 sites from these workers. In summary, the total paleomagnetic sampling survey is as follows: mafic sample sites, 535; mafic cinder cones sampled, 440; silicic and intermediate sites sampled, 115; silicic and intermediate eruptions sampled, >100.

We obtained oriented core samples with a portable rock drill similar to that described by Doell and Cox (1965). We usually took 6 to 8 samples per site, but for units in which we needed well-defined magnetic vectors, we took as many as 24 samples. We measured sample orientations by a sun compass when possible and oriented all samples by a Brunton compass. Lightning has extensively remagnetized the volcanic rocks, and so we preferred to sample oxidized vent rocks rather than lava flows, as discussed below. In some instances, minor rotations appear to have occurred in the tops and flanks of some block flows, many of which are andesitic to dacitic. We could sample some vents only from large bombs protruding through loose cinders. If samples from bombs yielded discordant data, the samples were presumed to represent slumped or rotated material; for this reason, several sites were not included in the data set.

Owing to the strong magnetization of most of the rocks sampled, measurements were made using either (1) a high-RPM, air-driven spinner magnetometer on 2.5-cm-diameter samples weighing generally 15 to 25 g or (2) a superconducting magnetometer on wafer-shaped samples 2.5 cm in diameter, 3 to 7 mm thick, largely weighing 3 to 8 g. Even so, some of the basalt samples have natural remanent magnetization (NRM) intensities beyond the range of the instrument, especially those with a strong lightning-induced, isothermal remanent magnetization (IRM) component. For cross-reference checking, we measured some samples with both instruments. Nearly all samples were subjected to alternating field (AF) demagnetization. Most samples were demagnetized stepwise at intervals of 250-Oe peak field to a maximum of 1,000 Oe. The number of steps used was based on the AF field required to remove most of the IRM component. Samples that probably retain a large component of IRM, as indicated by either high magnetic intensity or large deviation of direction from the majority of directions at a given sample site, were not included in calculations of the average direction of magnetization. This selection process did not alter any polarity determinations; however, data from ~15 sample sites

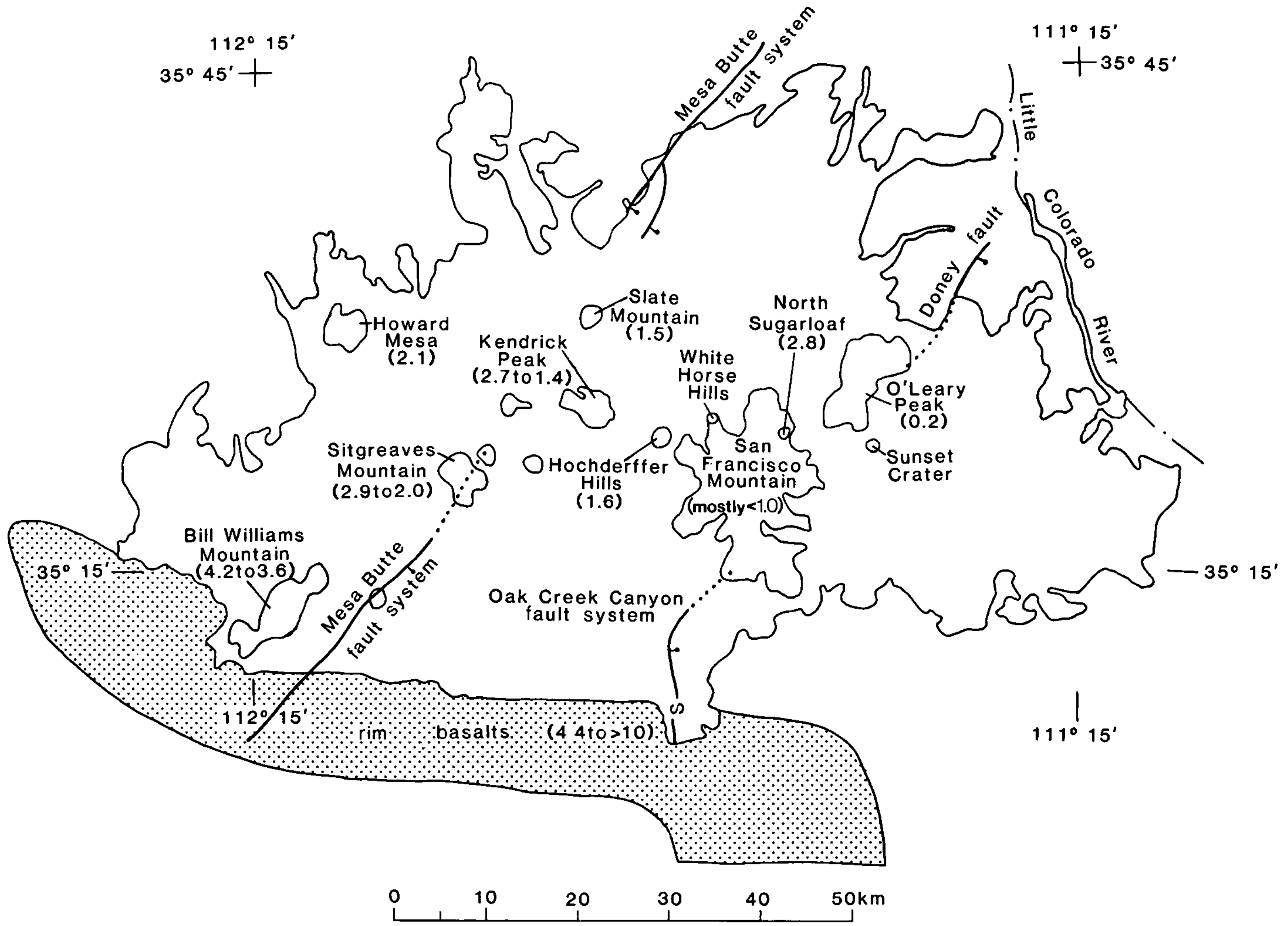

Figure 2. The San Francisco volcanic field and its silicic and intermediate centers (outlined within field), major structures, and northern extent of "rim basalts." Figures (in m.y.) indicate K-Ar ages of centers.

were insufficiently coherent to determine a polarity and were discarded. Average directions of magnetization for all inferred Matuyama and Brunhes mafic vents and flows at optimal demagnetization are shown in Figure 3.

MAGNETIC PROPERTIES OF THE VOLCANIC ROCKS

Magnetic studies of volcanic rocks in the San Francisco field (Babbitt, 1963; Coe, 1967; Strangway and others, 1968; Champion, 1980) showed that the major magnetic component in the basaltic lava flows is borne by titaniferous magnetite. This mineral has a Curie point generally between 400 and 550 °C, depending on the titanium content. All of the volcanic rocks studied, including dacitic blocks in pyroclastic flows, apparently came to rest at sufficiently high temperatures for their thermoremanent magnetization (TRM) to have been acquired in place. Emplacement temperature, then, was not a factor in sample-site selection.

The basalts sampled generally have NRM intensities of 10^{-3} to 1 G/cm^3, made up of TRM and IRM components. The components depend on a sample's dominant magnetic mineral phase and proximity to lightning strikes. Despite our efforts to avoid magnetic anomalies resulting from lightning strikes, the NRM's of most samples taken from lava flows are high in intensity and dominated by an IRM component. Samples taken from road-cuts, cinder pits, and oxidized vent material generally have low NRM intensities and only minor IRM overprints. Hematite is the primary magnetic mineral in the oxidized spatter, tuff, and cinder bombs sampled on the cinder cones. The coercivity of hematite

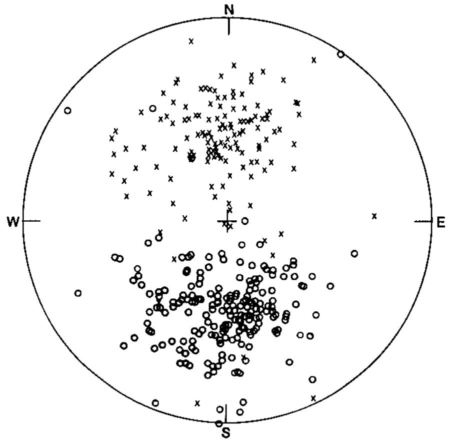

Figure 3. Equal-area plot of magnetic vectors of mafic sites inferred to be of either Brunhes or Matuyama chronozone. Crosses, positive inclination; circles, negative inclination. Vectors derived by averaging magnetic-field directions from optimally demagnetized samples from each site.

is sufficiently high that, despite the increased exposure to lightning on the rims of cinder cones, samples with magnetization dominated by hematite are relatively free of IRM.

POLARITY CHRONOSTRATIGRAPHY

Determination of Chronozones

The polarity time scale of Mankinen and Dalrymple (1979) for the past 5 m.y. provides the primary basis for polarity-chronostratigraphic correlation of Pliocene-Pleistocene rocks. The time scale is based on a statistical analysis of K-Ar ages and on magnetic polarity determinations that meet strict requirements of precision. The Brunhes, Matuyama, Gauss, and Gilbert chronozones defined originally by Cox and others (1964) are the principal units for which magnetostratigraphic correlations within the San Francisco volcanic field have been attempted by most workers. Although subchronozones such as the Jaramillo and Olduvai are represented in the field (T. C. Onstott, 1977, personal commun.), in most cases sufficient K-Ar and stratigraphic controls were not available for us to consistently identify the volcanic units belonging to these subchronozones. Age control, moreover, was insufficient for consistent distinction between Gauss and Gilbert (about 5.0 to 2.48 Ma) rocks. We therefore grouped rocks belonging to these chronozones with a few older rocks and considered their age to be pre-Matuyama.

Polarity determinations (Figs. 4 and 5), K-Ar ages, and stratigraphic relations provided the primary bases for our assignment of volcanic units to chronozones. Most of the K-Ar ages cited in Figure 5 are from the compilation of Luedke and Smith (1978) and are based on the work of Damon (1966), Damon and others (1974), and McKee and others (1974). These ages were slightly revised to reflect new decay constants (Dalrymple, 1979). Many additional K-Ar ages (P. E. Damon and M. Shaffiqullah, unpub. data; E. H. McKee, unpub. data) were critically important in establishing the volcanic stratigraphy and in making assignments to chronozones. Units dated by K-Ar were assigned to a single chronozone if the one standard-deviation interval included only that chronozone; otherwise, geomorphic or contact relations of the given unit with one or more dated units were used to ascertain the polarity zone.

Field evidence for local volcanic stratigraphy included superposition relations, lithologic correlations, geomorphic preservation, degree of weathering, and relative elevations of erosion surfaces that underlie the volcanic rocks. Fresh cinder cones and rough-surfaced lava flows in the eastern part of the field are clearly younger than the eroded vents with exposed feeder dikes and the smooth-topped flows in the western parts. Near the Little Colorado River (Fig. 2), late Quaternary rates of downcutting have been rapid enough to enable distinction of younger flows in stream bottoms and on successively higher terrace levels above the present drainage. These relations provided a basis for a relative-age classification by Colton (1936) and, more recently, for a stratigraphy for the eastern part of the volcanic field developed by Moore and others (1976). Radiometric ages indicate that lavas and tephra of the Tappan, Merriam, and Sunset stages of Moore and others (1976) fall in the Brunhes chronozone. Lavas dated as Woodhouse age by these workers can be shown on the basis of magnetic polarity and K-Ar ages to be-

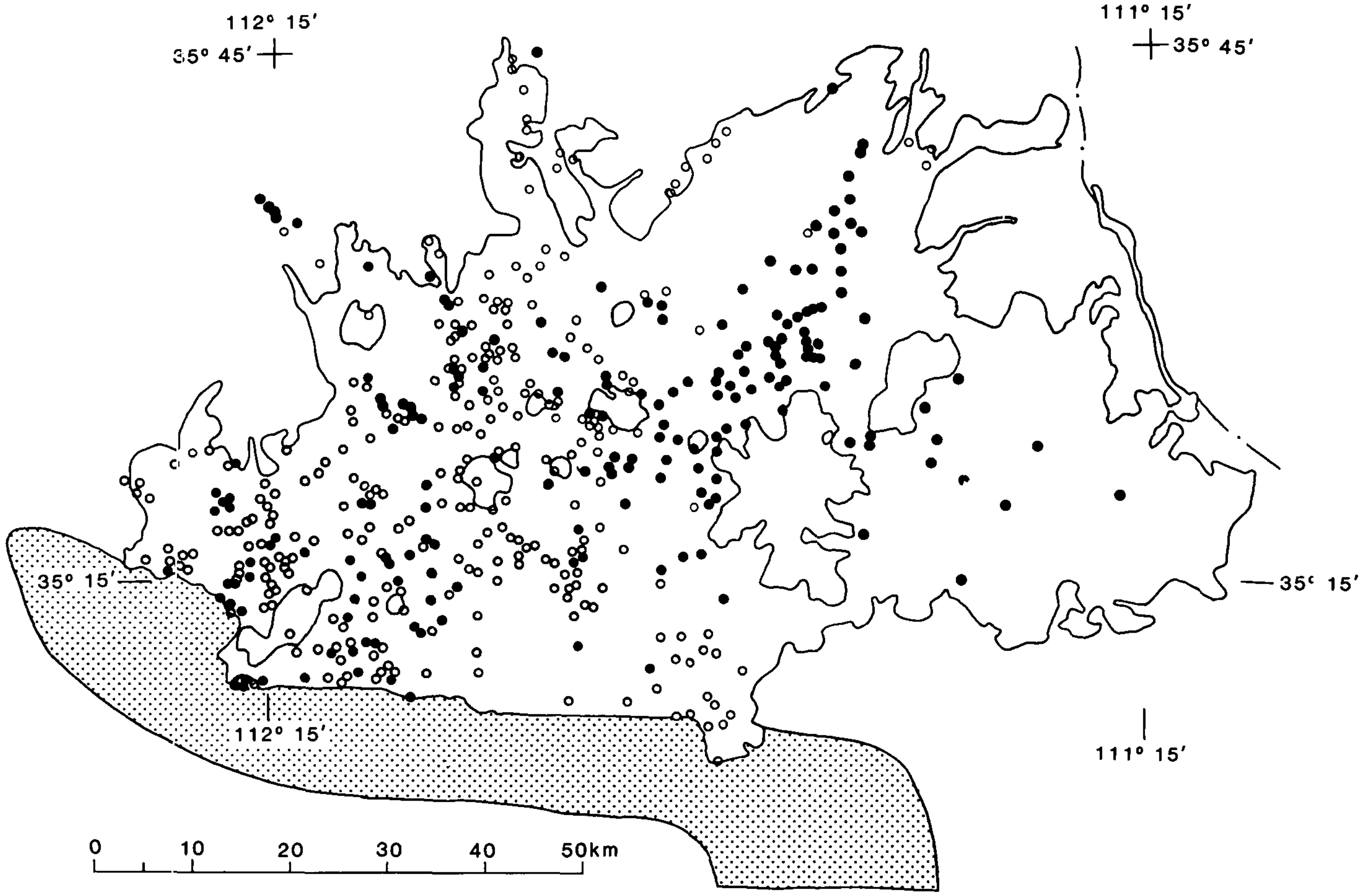

Figure 4. Paleomagnetic polarities measured in mafic vents in the San Francisco volcanic field. Solid circles, normal polarity; open circles, reverse polarity. Some vents occur within silicic centers (outlined).

long to the older part of the Brunhes or the Matuyama. All volcanic units in the eastern part of the volcanic field suspected of being pre-Brunhes in age were studied for paleomagnetic polarity, and most were analyzed radiometrically; units in the eastern part of the volcanic field known to be of Brunhes age were left unsampled.

In the central and western parts of the volcanic field, superposition relations were used extensively in deciphering the magnetostratigraphy. When superposition relations are combined with radiometric ages and paleomagnetic polarity data, chronozone determinations can be made for most vents. Some vents were correlated on the basis of similar lithology and proximity to vents of known age. Cinder cones having the same rock type are commonly in clusters or linear patterns and can be interpreted as the products of a single eruptive episode. For example, Sunset Crater and an associated group of vents along a northwest trend probably all erupted within a period of 200 yr (Champion, 1980, p. 50). These cinder-cone durations are much shorter than those of the silicic centers, most of which have eruptive histories spanning ~1 m.y. (Damon and others, 1974). Polarity-chronostratigraphic assignments were made for all mafic vents, most of the lava flows, and most intermediate to silicic volcanic units (Figs. 6 and 7).

Rocks of Pre-Matuyama Age

Rocks of the Gauss and Gilbert chronozones (about 5.0 to 2.48 Ma) are located mainly in the western extremity of the volcanic field (Fig. 6). Most volcanic rocks older than 5 m.y. along the southern margin of the field were considered to be part of the rim basalts. The nearly equal age span for normal and reverse subchronozones and the large number of subzonal polarity changes make separation of Gauss- and Gilbert-age rocks difficult without systematic radiometric-age control. K-Ar ages are abundant for silicic volcanic units but sparse for basalts erupted between 5.0 and 2.5 Ma. A total of 140 basaltic cinder cones was sampled; 61 have normal polarity, and 79 are reversed. Four flows and a tuff bed of similar age, the vents of which are unknown, were sampled. Seven cinder cones that we consider pre-Matuyama in age were unsampled.

The majority of pre-Matuyama basalt vents occur in an area of >300 km^2 in the southwest corner of the volcanic field, northwest of Bill Williams Mountain (Fig. 6). Of the vents sampled in this area, 17 are normal, and 48 are reversed. Flows along the east edge of the area are overlain by Matuyama-age flows.

East and northeast of Bill Williams Mountain, the eastern margin of the pre-Matuyama zone consists mainly of units of normal polarity

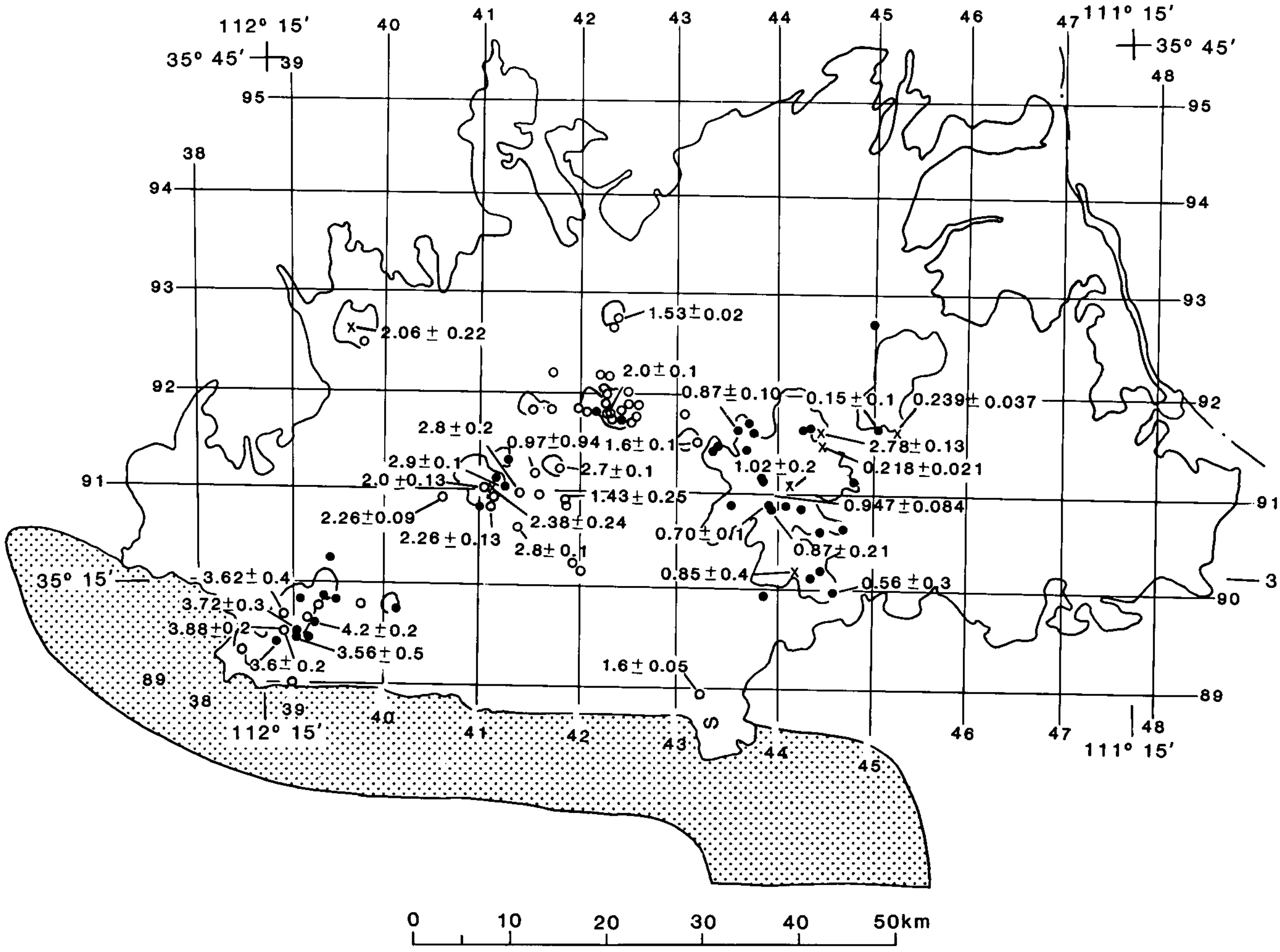

Figure 5. Paleomagnetic polarities and K-Ar ages in m.y. (chiefly from Luedke and Smith, 1978) of intermediate to silicic sites in this study; K-Ar ages revised to new decay constants (Dalrymple, 1979). Solid circles, normal polarity; open circles, reverse polarity; crosses, polarity undetermined. Universal Transverse Mercator (UTM) co-ordinates shown by 10-km grid.

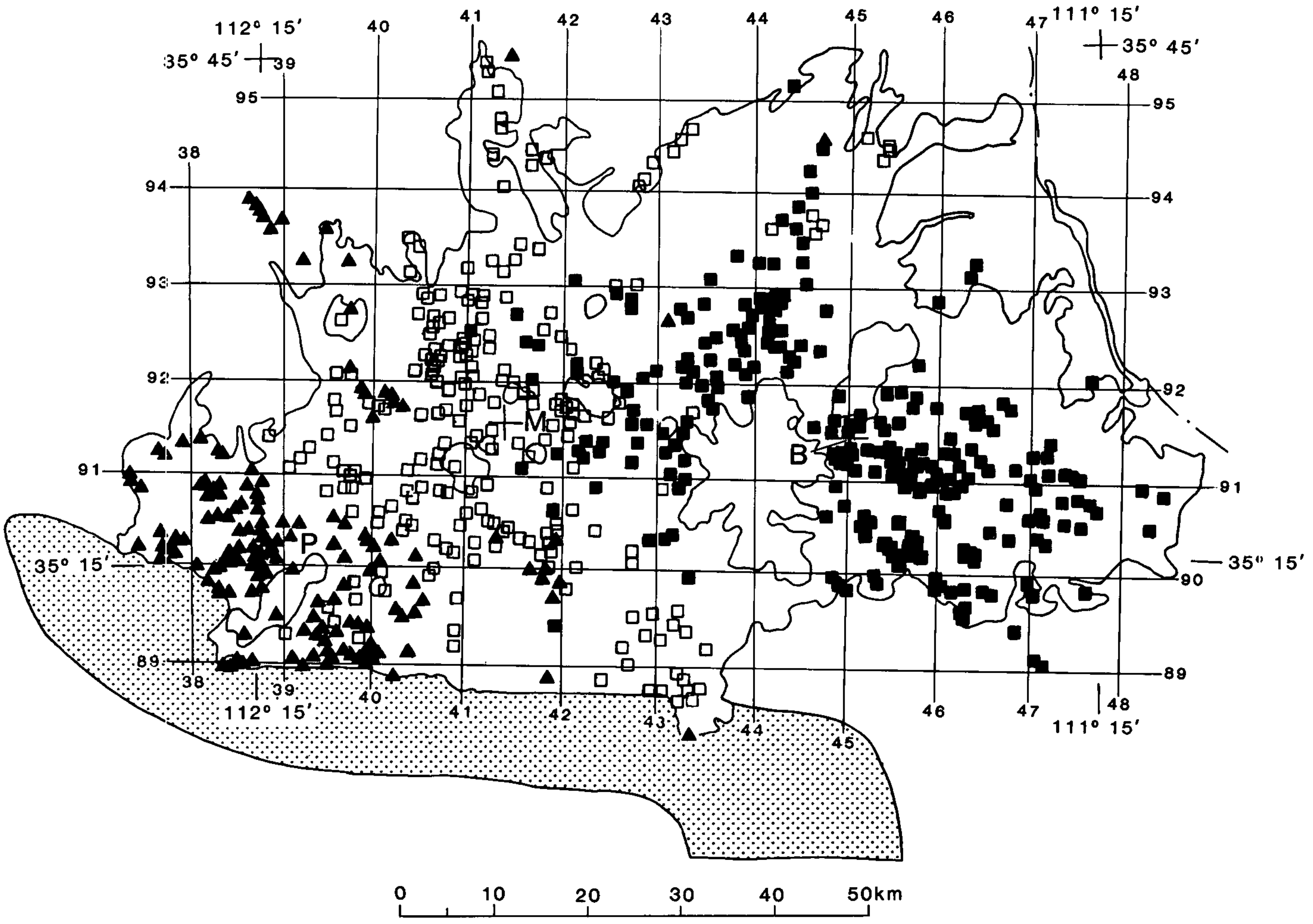

Figure 6. Distribution of mafic vents assigned to late Cenozoic chronozones. Solid squares, Brunhes chronozones; open squares, Matuyama chronozone; triangles, pre-Matuyama (Gauss and Gilbert) chronozone. Some vents occur within silicic centers (outlined). Crosses show centroid positions and axial lengths of the 95% confidence-interval ellipses for the Matuyama (M) and Brunhes (B) vents; P shows approximate centroid position for pre-Matuyama (about 5 to 2.48 Ma) vents. Note clear temporal progression of volcanism from southwest to northeast (P to M) and west to east (M to B). UTM co-ordinates shown by 10-km grid.

(Gauss chronozone), overlapped by reversed-polarity vents of probable Matuyama age. The pre-Matuyama zone has 20 vents of normal polarity and 22 of reversed polarity. The lack of systematic stratigraphic control in this area allows for the possibility that some may be Matuyama.

As shown in Figures 4 and 6, other pre-Matuyama vents are scattered in and adjacent to the volcanic field. An alignment of seven vents, five of normal polarity, is located outside the extreme northwest corner of the volcanic field. These vents are severely eroded and thus considered to be pre-Matuyama. Normal-polarity vents (8) south of Howard Mesa stratigraphically underlie surrounding reversed-polarity units of Matuyama age, including the Howard Mesa andesite of K-Ar age 2.06 ± 0.22 m.y. Six vents of the Volunteer Mountain complex (not shown) southeast of Sitgreaves Mountain are aligned along a northwest trend. They are part of a compositionally distinct assemblage that includes the younger Volunteer Canyon basalts (4.42 ± 0.45 m.y.). In addition, their eroded appearance and relative position beneath basalts of Matuyama age suggest placement within the pre-Matuyama.

The silicic rocks of pre-Matuyama age consist of the Bill Williams Mountain dome complex and nearby domes to the south and east and also a minor, early, eastern part of the Sitgreaves Mountain dome complex and nearby domes to the east (Fig. 5). Of 27 sampled locations for which polarity was determined, 18 have normal polarity. Pre-Matuyama silicic bodies have four published K-Ar ages for sites on and east of Sitgreaves Mountain (2.9 to 2.7 m.y.) and six on Bill Williams Mountain (4.2 to 3.6 m.y.).

Rocks of the Matuyama Chronozone

The Matuyama chronozone, of dominantly reversed polarity, spans the period between 2.48 and 0.73 Ma. The normal-polarity Jaramillo, Olduvai, and Réunion Events make up only ~0.32 m.y. of the Matuyama.

Matuyama-age units are found primarily in the western half of the volcanic field (Fig. 6). Of 220 mapped Matuyama vents, 173 have reversed polarity, 27 have normal polarity, and 20 do not have polarity determinations. Several Matuyama vents probably underlie younger rocks in the vicinity of San Francisco Mountain, as evidenced by the reversed polarity and K-Ar

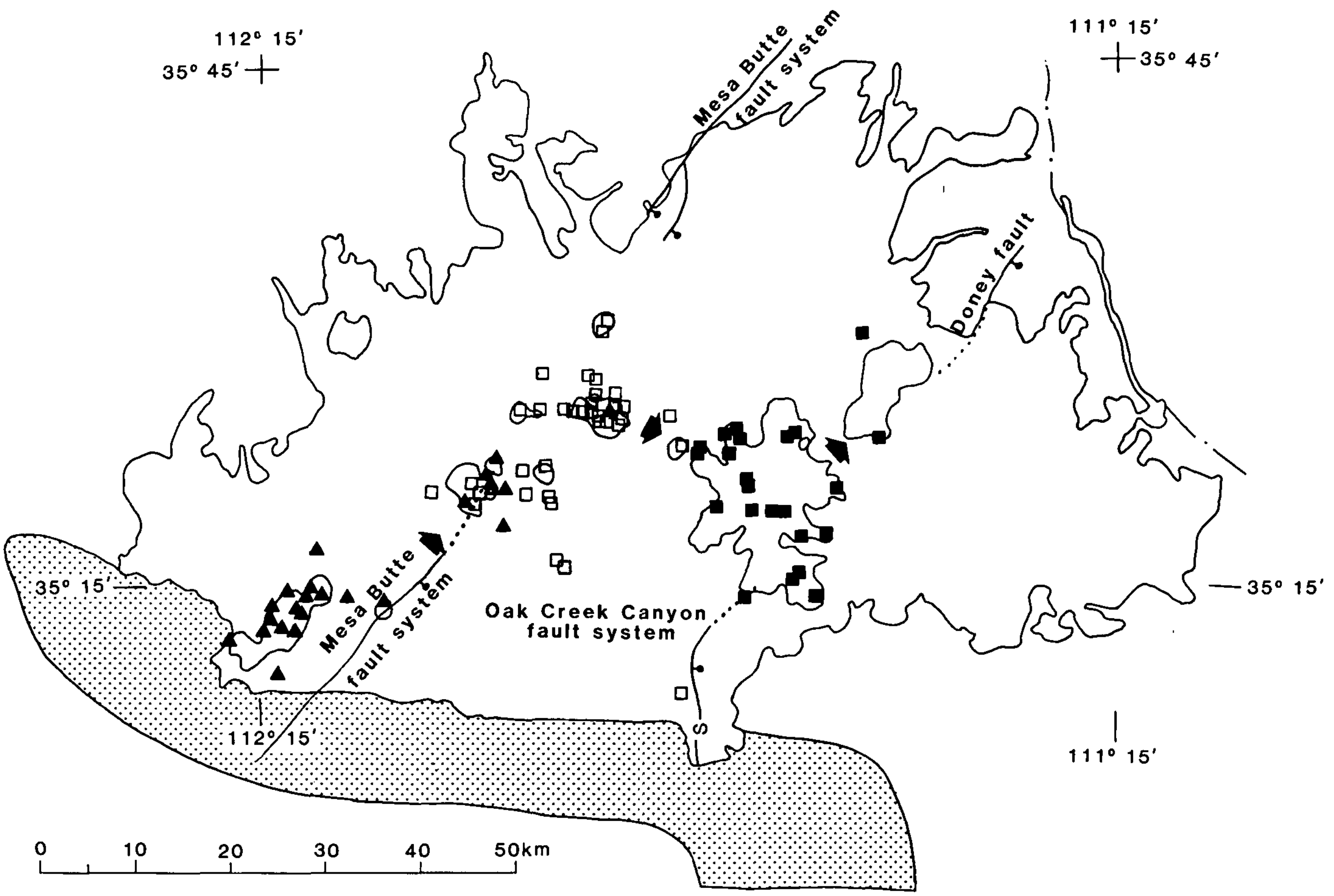

Figure 7. Inferred chronozone ages for silicic and intermediate sample sites within the San Francisco volcanic field. Solid squares, Brunhes chronozone; open squares, Matuyama chronozone; triangles, pre-Matuyama (Gauss and Gilbert) chronozones. These ages illustrate virtually the same temporal migration of volcanism (arrows) as do ages of the mafic rocks (Fig. 6).

dates (0.89 to 0.807 Ma) of lowermost flows (not shown) exposed along the eastern periphery of the volcanic field. In all, 16 flows without exposed vents were sampled.

Many of the Matuyama-age cinder cones are clustered and elongated along northwest, north, and northeast trends. Mafic units dated by K-Ar as Matuyama in age include three vents west and south of Sitgreaves Mountain and the flows of the Woodhouse Stage in the extreme eastern part of the volcanic field. Averaged magnetic directions determined in this study for 227 of the 236 Matuyama basaltic sites ascertained are shown (along with directions for Brunhes sites) in Figure 3.

Most of the intermediate and silicic rocks of the Matuyama chronozone lie along the northeast-trending Mesa Butte fault system, northeast of pre-Matuyama silicic domes. Also considered to be within this chronozone (Fig. 5) are four of the silicic domes on Sitgreaves Mountain (2.9 to 2.0 Ma), all but one of the nine sampled domes on Kendrick Peak (2.7 to 1.4 Ma; Wolfe and others, 1983), the Slate Mountain dome, five isolated domes east of Sitgreaves Mountain, and the Howard Mesa andesite; all but two of these sites have reversed polarity. A lower stratum of San Francisco Mountain and North Sugarloaf Mountain on its east flank yielded K-Ar dates of 0.947 ± 0.084 and 2.78 ± 0.13 Ma, respectively, and have not yet been sampled for magnetic polarity.

Rocks of the Brunhes Chronozone

Brunhes-age (0.73 Ma to present) vents dominate the eastern half of the volcanic field (Fig. 6). Altogether, 243 vents were designated Brunhes in age, of which 100 vents or associated flows, all of normal polarity, were sampled. K-Ar control is more comprehensive for these rocks than for older basalts in the field; furthermore, age relations based on morphology are well developed for part of this area. Brunhes flows without exposed vents (14) were also sampled.

More than 100 vents east of San Francisco Mountain were not sampled, because their age has been interpreted to be <0.7 m.y. on the basis of geomorphology, stratigraphy, and K-Ar dating (Moore and others, 1976); they are therefore considered to be of Brunhes age.

Silicic to intermediate units in the Brunhes zone include most of the San Francisco Mountain complex, White Horse Hills, and O'Leary Peak. Many samples from these units have had K-Ar age determinations, and all samples have normal polarity. Although the White Horse Hills rhyolite yielded a pre-Brunhes age of 0.87 ± 0.10 m.y., its intrusion deformed andesites of San Francisco Mountain that are ~0.4 m.y. in age, and therefore the rhyolite has been interpreted as Brunhes in age.

PATTERNS OF VOLCANISM

Distribution of Basaltic Vents

The inferred chronostratigraphy based on polarity developed in this study can now be viewed in a context of spatial and temporal patterns of volcanism. We analyzed statistically the spatial distribution of the basaltic vents (mainly cinder cones) of the Matuyama and Brunhes chronozones in reference to Universal Transverse Mercator (UTM) co-ordinates. The volcanoes of both chronozones are approximately normally distributed in the north-south and east-west directions (Fig. 6). The mean Matuyama vent location (centroid position) is between Bull Basin Mesa and Sitgreaves Mountain; for this location, the 95% confidence interval (the ellipse in which the true mean has a 95% probability of occurring) is 1.7 km east and west and 2.5 km north and south (Fig. 6). The standard deviation of the mean is 12.6 km east and west and 15.4 km north and south. The locations of partly buried Matuyama-age vents west of San Francisco Mountain and of proximally buried Matuyama-age flows (not shown) along the east edge of the volcanic field imply that vents of this chronozone underlie Brunhes-age lavas in the vicinity of San Francisco Mountain. The mean Brunhes vent location (centroid position) is near Sunset Crater and has a 95% confidence interval of 1.4 km east and west and 2.0 km north and south (Fig. 6). The standard deviation of the Brunhes vent population is 15.9 km east and west and 10.9 km north and south. The population is elongate northwestward. Our analysis may not include all pre-Matuyama-age vents in the study area, and so only an estimated mean vent location is shown at P in Figure 6. About 20 vents of Merriam and Sunset age have been identified within the volcanic field. Their centroid position coincides approximately with the centroid of all of the Brunhes-age vents.

Crustal Stress and Magma Ascent

Magma ascent and faulting along all major structural trends occurred throughout the history of the volcanic field, and thus caution is needed when analyzing stress conditions based on volcanic alignments. Thompson and Zoback (1979) inferred that the least horizontal principal stress was oriented N32°E, on the basis of an alignment of vents that include Sunset Crater. In view, however, of the evidence of recent normal offset along the Mesa Butte and Oak Creek Canyon fault systems and of the wide range of cinder-cone alignment, we suggest that the horizontal principal stresses were nearly equal in the map area during the evolution of the volcanic field. If this is so, orientation of volcanic lineaments was controlled solely by local crustal fractures. Horizontal offsets between magma source and eruption site probably were mainly a function of the lithospheric fracture spacing, and, if the inferred crustal-stress state was indeed horizontally isotropic, they were in random directions. A mean eruption location thus should closely reflect the location of the magma source. In the Mesa Butte and Oak Creek fault systems, larger volumes of magma could rise to upper-crustal levels and to the surface because of the fractures, weakness, and depth of the systems (Shoemaker and others, 1978). The silicic and intermediate melts that developed in these systems then inhibited ascent of mafic magma. For this reason, we address the migrations of mafic and silicic volcanism separately.

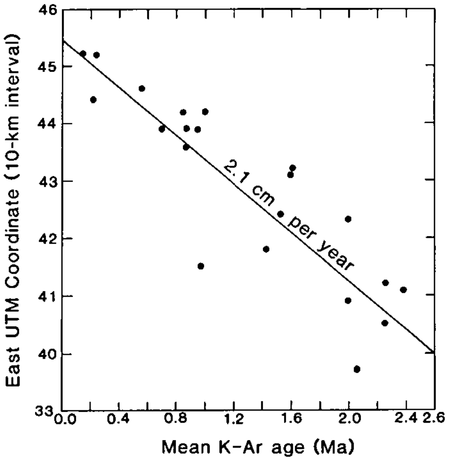

Figure 8. K-Ar ages versus east UTM co-ordinates for silicic rock samples <2.5 m.y. in age (Matuyama and Brunhes chronozones). For this analysis, only 1 age with 1.0 Ma or better precision was chosen for each of 21 sites from the compilation of Luedke and Smith (1978). The least-squares regression line (for which the correlation coefficient, R^2, equals 0.76) indicates an eastward migration rate of volcanism of 2.1 cm/yr.

Temporal Progression of Volcano Locations and of Rates of Vent Production

The combined chronostratigraphic data sets for mafic and intermediate-silicic lavas indicate that the volcanic activity that produced the San Francisco volcanic field migrated eastward with time (Figs. 6, 7). The initial direction of migration, from about 5 Ma until early in Matuyama time, was northeastward. From Matuyama time to the most recent eruptions, the average trend has been eastward, coinciding with an eastward decrease in the K-Ar ages of the silicic rocks (Fig. 8). The locations of the silicic rocks, however, probably have been strongly influenced by deep-crustal structures that may have stabilized the loci of volcanic activity for hundreds of thousands of years. Eastward progression nonetheless is evident in the shift of silicic volcanic activity from the Mesa Butte fault system to the Oak Creek fault system during late Matuyama time (Fig. 7). Both the silicic and mafic extrusives thus followed the same trends; also, cinder cones are generally of the same age as are the silicic units they surround.

The following examples indicating the time-space association of silicic centers and basaltic vents are illustrated in Figures 6 and 7. Bill Williams Mountain is dominantly composed of pre-Matuyama dacite domes and flows, and it is enclosed within a broad, northwest-trending belt of pre-Matuyama basaltic cinder cones. Sitgreaves Mountain rhyolites and nearby silicic domes are pre-Matuyama to early Matuyama (Fig. 7); the only exposed basaltic vents immediately surrounding the mountain are Matuyama in age (Fig. 6). Sitgreaves Mountain is situated at the intersection of the Mesa Butte fault and a northwest-trending zone of both pre-Matuyama and Matuyama cinder cones that extends from northwest of Howard Mesa to Volunteer Canyon. The intermediate and silicic rocks of Kendrick Peak and neighboring silicic domes (all dominantly Matuyama) are in a field of Matuyama-age and a few Brunhes-age cinder cones. The silicic centers of San Francisco Mountain and O'Leary Peak, both mainly Brunhes in age, are in an area of cinder cones and lava flows that are almost entirely Brunhes. Lower strata in San Francisco Mountain and associated older silicic domes are Matuyama or older; furthermore, a few Matuyama basalt flows exposed along the east edge of the volcanic field probably were extruded from the vicinity of San Francisco Mountain.

The eastward progression of silicic volcanism was estimated by using the K-Ar data of Luedke and Smith (1978). All units were included that have mean ages of <5 m.y. and <1.0-m.y. standard deviation about the mean. If more than one age qualified per sample site, the age that agreed best either with field relations or with a new, unpublished age was selected. A least-squares regression of the 32 ages selected (Fig. 5) as a function of their north and east UTM co-ordinates yielded a rate of migration of 1.6 cm/yr on an azimuth of N75°E. For the Matuyama and Brunhes chronozones (<2.5 Ma), 21 K-Ar ages were selected; these ages regressed to an average 2.1 cm/yr (Fig. 8) on an azimuth of S89°E. In contrast to the cinder-cone data, this analysis does not draw from a comprehensive, approximately volume-weighted sample, and so the calculated migration rates and trends should be viewed as low-precision estimates. These trends of migration based on K-Ar ages, however, are similar to those observed for the chronozones inferred for the silicic centers (Fig. 7). Possible renewal of northeastward progression during the late Brunhes is suggested by the

TABLE 1. COMPUTED MEASUREMENTS OF VOLCANIC ACTIVITY FOR THE SAN FRANCISCO VOLCANIC FIELD

Rock type	Age (Ma)	Volume (km^3)	Volume rate (10^{-6} km^3 yr^{-1})	Heat-production rate* (10^{12} erg s^{-1})
Basaltic rocks	5.00–2.48 (pre-Matuyama)	47	19	10
	2.48–0.73 (Matuyama)	72	41	21
	0.73–0.10 (early Brunhes)	210	330	170
	0.10–0.00 (Merriam and Sunset)	3.5	35	18
Silicic and intermediate rocks†	5.00–3.00	105	53	28
	3.00–1.00	147	74	39
	1.00–0.25	860	1,100	570
	0.25–0.00	40	160	84
All types	5.00–3.00	152	75	39
	3.00–1.00	219	110	57
	1.00–0.25	1,070	1,400	730
	0.25–0.00	43.5	180	92
	5.00–0.00	1,485	300	160

*Based on heat content of 400 cal cm^{-3}.

†Volumes are sums of measured surface volumes and volumes of associated intrusive rocks estimated by multiplying surface volumes by a factor of six. Estimation method and age categories explained in text.

location of the O'Leary Peak complex northeast of the older San Francisco Mountain center.

In order to determine a rate of migration for the cinder cones, the average UTM co-ordinates described above were used for the Brunhes, Matuyama, and pre-Matuyama vents. Although volcanism was probably intermittent in time and space, the large number of vents represented in each chronozone permits the assumption that these averaged vent locations correspond to the central loci of volcanic activity for the mean age of each chronozone. Given the 1.24 m.y. between the mean ages of the Matuyama (1.605 m.y.) and the Brunhes (0.365 m.y.), and the 36.4 ± 3.7 km (95% confidence interval) and approximate east-west orientation between centroid positions of the Brunhes and Matuyama vents (Fig. 6), we calculate that movement took place at an average rate of 2.9 ± 0.3 cm/yr along an azimuth of S87° ± 5°E. This direction coincides with the progression of the silicic centers for the same time interval. A similar rigorous analysis was not performed for pre-Matuyama rocks, because the older limit of their age is not precisely known, and because other cinder cones south of the mapped area possibly erupted during the same time interval. The approximate centroid of pre-Matuyama volcanism within the volcanic field is shown in Figure 6. If the approximation is accurate, and if the ages of most vents are <5 m.y., then the same northeastward progression of volcanism occurred for pre-Matuyama and Matuyama mafic vents as that suggested for the silicic rocks at a rate of ~1.2 cm/yr.

The rate of vent production also changed as the volcanic field evolved. The field contains more Brunhes vents than either Matuyama or pre-Matuyama vents, even though Brunhes time was of shorter duration. Vent production during the Brunhes was ~1 per 3,000 yr, an increase over that of the Matuyama (~1 per 8,000 yr) and pre-Matuyama (~1 per 17,000 yr). The formation of only ~20 vents during the Merriam and Sunset stages, however, indicates that vent production has decreased since 0.1 Ma.

Volume Rates of Effusion and Heat Production

Volume rates of effusion are correlative with vent-production rates for both basaltic and silicic rocks, but their changes are even more dramatic (Table 1). The rates peaked early in Brunhes time. They probably have a smaller range than calculated, because buried pre-Brunhes age lavas are included in the Brunhes calculations in some areas.

Estimates of heat-production rates (Table 1) were made for both basaltic and silicic/intermediate rocks within four age groups. The rates for basalts are based on convective heat transfer of the observed volumes of rocks at the surface. No estimate was made for associated intrusive deposits,but intrusives were taken into account for the silicic/intermediate rocks. San Francisco Mountain may be underlain by a magma chamber that is still hot (Smith and Shaw, 1975); a low-velocity body with a volume of ~300 to 700 km^3 has been identified from seismic studies (Stauber, 1982). Stauber's models for such a body include a cool silicic and even a hot to partly molten andesitic-to-basaltic plutonic complex beneath San Francisco Mountain at a depth of ~9 to 34 km below sea level. If the plutonic complex has a volume of 500 km^3 and a slightly higher density than do surface rocks, then its equivalent surface volume is about 6 times greater than the estimated pre-eroded surface volume of the mountain (~94 km^3; Holm, 1984). We thus have used the factor of six to estimate subsurface magma quantities associated with other silicic centers of the volcanic field. On the basis of the estimation factor for the associated plutonic bodies and the measured volumes of the volcanic centers, we calculate that the silicic/intermediate rocks account for more than two-thirds of the volume and heat production of the field (Table 1). As the silicic/intermediate rocks show the same temporal progressions in eruption as do the basalts, the silicic data can be combined with the basaltic data.

The silicic/intermediate rocks were grouped into time periods based on the periods of activity at the major eruptive centers. These time periods are somewhat different from the polarity chronozones of the basaltic rocks. As the silicic/intermediate rocks and their plutons account for most of the volume of magma generated, volumes of basaltic rocks erupted during specific time periods were placed into the age category for silicic and intermediate volcanism that matches most closely. The resulting adjusted rates for the basalts cause the combined rates for all types (Table 1) to be slightly higher for the periods 5.00-3.00 and 1.00-0.25 Ma and slightly lower for the periods 3.00-1.00 and 0.25–0.00 Ma than would be expected if the time periods corresponded exactly. These rates are useful for the integrated study of magmatism associated with the volcanic field, as discussed below under "Magma Source and Generation."

Present heat-flow measurements for the San Francisco field have a mean of 27 ± 5 milliwatts/m^2, although ~100 milliwatts/m^2 would be expected, given the field's recent volcanic activity (Sass and others, 1982). Sass and others proposed that the deficiency in observed heat flow is caused by lateral circulation of heated ground water to areas outside the volcanic field. Discharge of ground water from most of the volcanic field (excluding parts of the southern and western edges) is at Blue Springs (north of map area in Fig. 2) on the Little Colorado River (Loughlin, 1983, Fig. 4). Blue Springs also drains ground water from other parts of the Little Colorado River valley; Loughlin estimated that the amount of discharge from the volcanic field is ~158 ft^3/s (4.47×10^6 cm^3/s), at a temperature of ~70 °F (21 °C). Assuming that this water originates from precipitation having a mean temperature of 7 °C (the mean air temperature recorded by the National Weather Service at Flagstaff), we can calculate that the power drawn from the volcanic field is 2.62×10^8 watts. If the average heat-flow deficiency of the volcanic field is 70 milliwatts/m^2, then discharge of heated water at Blue Springs accounts for heat loss from 3,740 km^2 (the approximate area of the field that has hydrologic discharge at Blue Springs). An estimate of 100 milliwatts/m^2 (2.5 heat-flow units) for current average heat flow for the San Francisco volcanic field is therefore appropriate.

Virtual Geomagnetic Pole Positions

Analyses of virtual geomagnetic pole (VGP) data were used to measure tectonic rotation and latitudinal translation of crustal blocks in western North America. In mid-Tertiary rocks west of the San Andreas fault, most evidence indicates large clockwise rotations and northward translations (Beck, 1980). Possible counterclockwise rotations have been observed in Miocene volcanic rocks east of the San Andreas fault in the Mojave block (south of the Garlock fault) and in the Basin and Range province of southwestern Arizona (Burke and others, 1982; Calderone and Butler, 1984). These studies were based on rocks older than those of the San Francisco volcanic field; also, the field lies in the Colorado Plateau tectonic province, which is considered to be a part of stable North America. It comes as no surprise, then, that our preliminary analysis of VGP positions and rotation and flattening statistics (Beck, 1980) indicates that no tectonic movement has occurred on this part of the Colorado Plateau for the past 5 m.y., on the basis of site-averaged magnetic vectors for rocks in the Brunhes, Matuyama, and pre-Matuyama chronozones.

DISCUSSION

Migration of Volcanism in Central and Northern Arizona

The paleomagnetic data presented here, combined with radiometric dating, detailed mapping, and volume measurements, enable the most detailed study of chronology and magmatism made thus far for a volcanic field as large as the San Francisco field. Now this migration can be assessed in the context of local and regional geology and tectonics.

Basaltic volcanism migrated northeastward from west-central Arizona onto the Colorado Plateau of northern Arizona during middle Miocene to early Pliocene time (Luedke and Smith, 1978). This migration crossed over a major lithospheric boundary zone between the Basin and Range and Colorado Plateau tectonic provinces (Thompson and Zoback, 1979). The San Francisco volcanic field lies along the northern edge of this zone (Fig. 1). As the migration of volcanism progressed, associated north-trending, high-angle, normal faulting diminished (Lucchitta and Suneson, 1983). Possible causes of this progression of volcanic activity include (1) movement of the North American plate over a deep-mantle thermal anomaly (hot spot); (2) erosion of the lithospheric keel beneath the Colorado Plateau by heating from the Basin and Range province (Best and Brimhall, 1974); and (3) propagation of volcanism along the Colorado Lineament, a major northeast-trending lithospheric fracture zone (Warner, 1978).

Migration of Volcanism in the Western United States and Hawaii

Oceanic volcano chains such as the Hawaiian Islands–Emperor Seamounts give clear evidence for temporal and spatial volcanic progressions that has been used to support the hypothesis that oceanic plates are moving over relatively fixed, deep-mantle hot spots (Morgan, 1972). Detailed analysis of changing rates of eruption, loci of eruption, and migration rates of volcanism of the Hawaiian volcanoes indicates, however, that volcanism has been cyclic and complex and can be explained by a model of self-sustaining zones of shear heating (Shaw, 1973). Volcanic progressions on the continents, however, have been more difficult to model because of greater complexities in crustal and mantle composition and structure, lower volumes of extrusives, and often poor age control. Some examples of continental volcanic fields for which migration has been proposed are briefly described below (see also Lipman, 1980; Smith and Luedke, 1984).

In the Great Basin, Cenozoic volcanism generally has progressed outward from a central region (Scott and others, 1971). In the Great Basin and Snake River Plain, three-rayed loci of volcanism may represent lithospheric rifting that emanated from a zone of thermal upwelling (Best and Brimhall, 1974). In eastern Nevada and western Utah, east-trending swaths of volcanism progressed southward from 43 to 6 Ma (Stewart and others, 1977). No migrations in volcanism were found within individual, east-trending zones of volcanic rocks; however, lack of precision and insufficient accuracy of radiometric data could mask any fine-scale progression. The inception of volcanism along the eastern Snake River Plain–Yellowstone trend has progressed northeastward at 3.5 cm/yr (Armstrong and others, 1975); this volcanism has been proposed to be the result of either movement of the North American plate over a subcontinental hot spot (Minster and others, 1974) or migration along a major northeast-trending structural and aeromagnetic lineament (Smith and others, 1974; Eaton and others, 1975). A nearly symmetrical pattern of volcanism originated at the same time and place as did the eastern Snake River Plain volcanism but has migrated northwestward to Newberry volcano in west-central Oregon (MacLeod and others, 1976). In a model describing the evolution of the Great Basin, Christiansen and McKee (1978) attributed this over-all pattern of volcanism to migrating zones of lithospheric extension and stress relief that intersect a northern transform boundary of the Great Basin.

Location of volcanic fields on the Colorado Plateau may also be controlled by major lineaments in the lithosphere (Eastwood, 1974; Luedke and Smith, 1978; Warner, 1978; Smith and Luedke, 1984). The Jemez zone of aligned volcanic centers extending from Sonora, Mexico, to northeastern New Mexico is composed of about a dozen loci of volcanism that indicate no over-all age progression (Laughlin, 1976). A long-lived mantle-plume origin for this alignment of volcanic centers thus is unlikely. Inception of hawaiite extrusion in volcanic rocks of the Uinkaret-Shivwits Plateau north of the Grand Canyon appears to have moved eastward over the past 7 m.y. at 1 cm/yr. Its movement has been attributed to eastward erosion of the Colorado Plateau's lithospheric keel due to convective heat flow associated with the Basin and Range province (Best and Brimhall, 1974). The volcanic fields on the Colorado Plateau are localized along linear zones of major structural weakness (Eastwood, 1974). Where these zones coincide with areas of high heat flow in the mantle or lower crust, they enable the rise of magma and eruptive activity. A synthesis of migrating volcanic loci in the western United States by Smith and Luedke (1984) indicates that east of the Great Basin province, northeastward or eastward migrations occur; west of the province, migrations are westward. Smith and Luedke suggested that these two migration directions can be explained, respectively, by southwestward motion of the North American plate over relatively fixed mantle sources and by westward advance of the keel of the North American plate.

Most volcanic fields on the Colorado Plateau do not show documentable migration, perhaps for one or more of the following reasons. (1) None occurred because of either lack of migration of the magma source or restriction along favorable conduits (for example, the Jemez zone). (2) The recorded eruptive lives of the volcanic fields are too short to show a clear progression. (3) Age-control data are insufficient to establish a temporal progression.

Magma Source and Generation

The major-element chemistry of the basaltic magmas erupted in the San Francisco volcanic field indicates an origin as partial melt from

TABLE 2. ESTIMATES OF PARAMETER VALUES FOR VISCOUS HEATING MODELS, HAWAIIAN VOLCANOES AND SAN FRANCISCO VOLCANIC FIELD (SFVF)

Location	Age* (Ma)	Heat-production rate† (10^{-6} erg cm^{-3} s^{-1})	Strain rate§ (10^{-14} s^{-1})	Shear stress (bars)	Viscosity (10^{20} poise)
Kauai	5.60	7	6	120	20
Kilauea	0.40–0.00	68	40	170	4
SFVF	5.00–3.00	2	2	110	60
	3.00–1.00	3	3	110	40
	1.00–0.25	42	5	84	20
	0.25–0.00	5	..	..	..

*Hawaiian ages cited in Jackson and others (1972).

†Volume normalized; SFVF rates based on total rates in Table 1 and 17,500 km^3 source volume.

§SFVF strain rates based on 20-km-thick shear zone and progression rates of 1.2, 2.1, and 2.9 cm yr^{-1}, respectively, for periods 5.00–3.00, 3.00–1.00, and 1.00–0.25 Ma.

Note: Data for Hawaiian volcanoes and calculation methods from Shaw (1973, Table 3).

upper-mantle material at the base of the lithosphere. Strontium isotopic data for the San Francisco volcanic field indicate a mantle source (Brookins and Moore, 1975). Lead systematics indicate contamination or derivation from material of 1,500 to 1,600 m.y. age (Everson, 1979, p. 185), which is about the age of Precambrian basement rocks in central Arizona.

There are two possible principal origins for the silicic magmas: fractionation of basaltic magma and crustal anatexis from heating by basaltic magmas. It is likely that both processes were important. The preponderance of rhyolite and the absence of rocks of intermediate composition at Sitgreaves Mountain may have resulted largely from crustal anatexis. On the other hand, andesites and dacites dominate at San Francisco Mountain. Wenrich-Verbeek (1979) offered compelling evidence that these last two rock types are related on the basis of crystal fractionation and may have an alkali-olivine basalt parentage. In either case, basaltic volcanism and intermediate to silicic volcanism have been coeval in the field; the presence of low-density, silicic crustal rocks may be indicated by association of the silicic centers both with broad, northeast-trending negative Bouguer anomalies (J. D. Hendricks, unpub. data) and with northeast-trending, low-residual aeromagnetic anomalies (Sauck and Sumner, 1970).

The progression of volcanism in the San Francisco field may be explained by two basic categories of models: (1) multiple source regions and (2) a single evolving and shifting source. The first category requires either multiple heat sources or movement of a single heat source relative to the mantle region from which the magmas were derived. We have as yet no method to evaluate or explain these possibilities, although they cannot be ruled out. The second type of heat source could include a fixed-mantle hot spot, a propagating fracture, or a zone of shear heating (Dalrymple and others, 1973). The early, northeastward migration in the volcanic field was directed, in part, by major northeast-trending crustal structures; thus, migration may be explained by propagation along fractures, perhaps in conjunction with another process. The later episode of eastward movement apparently was not guided by crustal fractures, leaving both the hot-spot and shear-heating models as possible alternatives. Of these, we favor the shear-heating model, because of the small size of the volcanic field and the lithospheric source region of the magmas. To test the merits of this hypothesis, we have developed a model for the evolving geometry and magma generation of the source region and have compared it with theoretical and applied studies of shear heating (Shaw, 1969, 1973).

Heat is produced by internal friction from flow of a viscous substance (viscous dissipation) and is a possible mechanism for producing lavas in the Earth's mantle (Shaw, 1969). In this process, thermal feedback occurs when cooling by conduction no longer keeps up with heat production. The extra heat raises the temperature, decreases viscosity and density, and produces melt from the host material. Such conditions will occur in the Earth's mantle if sufficient shear stress is applied (Shaw, 1969). Viscous dissipation in the mantle may be involved in the detailed evolution of migration and heat production of the volcanic rocks that compose the Hawaiian Ridge–Emperor Seamounts (Shaw, 1973).

In our model for the generation of the San Francisco field magmas by viscous heating, shearing was induced at the base of the lithosphere by stress from asthenospheric flow. Such activity may have been localized beneath the field by an increase in shear stresses due to rapid thickening of the lithosphere (which thins the zone of asthenospheric shear and increases the strain rate) and by a possible "bump" or other inhomogeneity at the base of the lithosphere. We can model the dimensions, heat generation, stress, strain rate, and melting relations of such a mass, if we assume that it is the source of heat production and if we know the dimensions, progression rates, and volume rates of the volcanic field.

The model bump is given a width of 35 km, derived from the approximate north-south width of the volcanic field in which the main volume of the volcanic rocks occurs. Its length is estimated to be ~25 km, derived from the duration of the major episode of volcanism of San Francisco Mountain (1.00 to 0.25 Ma) and the rate of volcanic progression (3 cm/yr) during the history of this center. Its estimated thickness of 20 km is based on the need for sufficient volume (17,500 km^3) from which the magmas could have been derived by partial melting. Unfortunately, no geophysical data of sufficient resolution and depth are available to indicate the existence of the proposed bump. On the basis of the estimate of 1,500-km^3 total magma volume (Table 1) for the volcanic field (66% unerupted), nearly 9% partial melting has occurred. Shaw (1973) estimated partial melting of the source for the southeastern Hawaiian volcanoes to be at least 4%, perhaps to >10%.

Calculated results of the viscous heating model are shown in Table 2. The strain rates for the periods 5.00 to 3.00 Ma and 1.00 to 0.25 Ma are based on volcanic propagation rates of 1.2 cm/yr and 2.9 cm/yr, respectively, from the centroid data for basalts. The volcanic propagation rate of 2.1 cm/yr for the period of 3.00 to 1.00 Ma reflects the average rate for Matuyama and Brunhes silicic rocks that is based chiefly on K-Ar ages within the Matuyama (Fig. 8). A precise rate cannot be determined for the period 0.25 to 0.00 Ma, because statistical uncertainties are too large. All values (except viscosity) for the San Francisco field model are lower than those for the Hawaiian models. For both models, the heat-production rate has increased exponentially with time. Strain rates increased faster, and viscosity decreased faster for the Hawaiian volcanoes than for the San Francisco field. Shear stress has increased for the Hawaiian model and decreased slightly for the San Francisco field. These values for the two models would be brought into closer agreement if the postulated bump source for the San Francisco field became thinner as it sheared, which would result in higher strain rates, higher shear stresses, and lower viscosity for the periods 3.00 to 1.00 and 1.00 to 0.25 Ma.

Hawaiian Ridge–Emperor Seamounts volcanic chains have eruptive durations of ~10 m.y., of which the latest episode (Kauai to Kilauea) has been active for nearly 6 m.y. (Jackson and others, 1972). In contrast, volcanism on the Colorado Plateau is more sporadic, and locations appear to be controlled by lithospheric inhomogeneities rather

TABLE 3. PROPOSED ABSOLUTE-MOTION VECTORS FOR THE NORTH AMERICAN PLATE IN NORTHERN ARIZONA AND VICINITY

No.	Azimuth	Rate (cm yr^{-1})	Model
1*†	S58°W	2.6	Best fit to hot-spot data (Minster and Jordan, 1978)
2†	N87°W	2.3	Staionary African plate (Minster and Jordan, 1978)
3	S82°W	3.7	Stationary African plate (Duncan and McDougall, 1976)
4	S60°W ± 20°	. .	Yellowstone trend (Minster and others, 1974)
5	N87°W ± 5°	2.9 ± 0.3	San Francisco volcanic field (this paper)

*Closely coincides with determinations for no-net-rotation and stationary Caribbean-plate models.
†Includes Yellowstone track as a hot-spot trend used in fitting procedure.

than by recurrence over a fixed-mantle location. Volcanism at Kilauea is, moreover, at present migrating at 30 cm/yr and requires a model that can invoke such high rates of movement, perhaps by counterflow between the lithosphere and asthenosphere, as suggested by Shaw (1973). Our lithospheric bump model accounts for both the differences and similarities of magma production and volcanic propagation between the Hawaiian chain and the San Francisco field. Kilauea volcanism is probably reaching a peak (Shaw, 1973), whereas we suspect that activity in the San Francisco field has been decreasing over the past 250,000 yr. This possible decrease may be explained by the pervasive depletion of the proposed mantle bump by partial melting and perhaps by decrease in shear stress due to assimilation of such a mantle bump into the asthenosphere.

Implications for Motion of the North American Plate

Earlier discussion indicated that migration of volcanism along the eastern Snake River Plain–Yellowstone trend may be due to expansion of volcanism along a major northeast-trending lineament system rather than to the propagation of a limited hot spot of activity. This pattern of volcanism has a symmetric counterpart of northwest-trending volcanic propagation in southeastern and west-central Oregon that relates to tectonic development of the Great Basin. Although migration in the San Francisco volcanic field has been relatively minor in space and time, it is well resolved and apparently has been free of guidance by crustal structures or intraplate tectonic movements since Matuyama time.

If either our mantle-bump theory or a hot-spot hypothesis is correct, then later migration in the San Francisco field was controlled principally by the motion of the North American plate over the fixed mantle. Based on the plate-motion analysis by Minster and Jordan (1978), the present-day absolute motion vector (best fit to hot-spot data) for the volcanic field is 2.6 cm/yr at S58°W (model 1 in Table 3). The hot-spot model includes the Snake River Plain as an absolute vector with a direction of S60°W. Alternatively, if the hot-spot model is based on the assumption of a stationary African plate (Burke and Wilson, 1972; model 2 in Table 3), we can predict a movement of 2.3 cm/yr at about N87°W, coincident with the direction of volcanic migration in the San Francisco field during the past 2.5 m.y. The predicted motions of the fixed–African-plate model fit reasonably well with inferred hot-spot motions world-wide, except that of the Snake River Plain (Minster and Jordan, 1978). According to the model of Duncan and McDougall (1976), motion and direction of the southern part of the North American plate are ~3.7 cm/yr at S82°W, with Africa fixed (model 3 in Table 3).

CONCLUSIONS

The progression of volcanism in the San Francisco volcanic field can be characterized as follows.

1. Migration of the centroid of volcanism has been shown to be statistically valid according to the distribution of K-Ar ages of silicic rocks and chronozone distributions of basaltic cinder cones.
2. Migration began in pre-Matuyama time to the northeast, centered along the Mesa Butte fault, at a rate of 1.2 cm/yr. Since early Matuyama time, volcanism has migrated eastward at 2.9 cm/yr.
3. The alignment of volcanoes along all major basement fault trends indicates that the horizontal principal stresses have been nearly equal.
4. An increase in rates of migration, cinder-cone production, and magma generation began ~5 m.y. ago and may have waned during the past few hundred thousand years.
5. The dominant bulk composition of extrusive rocks and their buried intrusive counterparts may be intermediate.

Plutonic masses at depth are probably associated with zones of high fracture density, such as intersections of major fault systems; silicic magmas may have been derived from partial melting of Proterozoic rocks or from fractionation of basaltic melts. The young plutons, particularly those beneath San Francisco Mountain, are assumed to account for the present-day apparent high heat flow of the volcanic field, for negative Bouguer gravity anomalies and low residual aeromagnetic anomalies over the silicic centers, and for a seismic-velocity anomaly beneath San Francisco Mountain.

The location of late Cenozoic volcanic fields along the southern margin of the Colorado Plateau in Arizona is strongly controlled by basement lineaments. Coincidence of such lineaments with thermal perturbations in the asthenosphere or lower lithosphere may be required for commencement of volcanic activity in the continental crust. These conditions are evidently met in the San Francisco volcanic field. In addition, a model of viscous heat generation caused by shearing in a basal lithospheric bump is in accord with the geophysical setting and the evolution and chemistry of the volcanic rocks of the field. Migration of volcanism in Matuyama-Brunhes time did not follow crustal trends and may reflect relative motion of the North American lithospheric plate over the stationary deep mantle.

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REFERENCES CITED

Armstrong, R. L., Leeman, W. P., and Malde, H. E., 1975, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225–251.

Babbitt, B. E., 1963, A paleomagnetic study of the San Francisco volcanic field, Arizona [M.Sc. thesis]: Durham, England, King's College, University of Durham, 58 p.

Beck, M. E., 1980, Paleomagnetic record of plate margin processes along the western edge of North America: Journal of Geophysical Research, v. 85, p. 175–179.

Best, M. G., and Brimhall, W. H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, p. 1677–1690.

Brookins, D. H., and Moore, R. B., 1975, Strontium isotope initial ratios from the San Francisco volcanic field, Arizona: Isochron/West, no. 12, p. 1–2.

Burke, D. B., Hillhouse, J. W., McKee, E. H., Miller, S. T., and Morton, J. L., 1982, Cenozoic rocks of the Barstow Basin area of southern California—Stratigraphic relations, radiometric ages, and paleomagnetism: U.S. Geological Survey Bulletin 1529-E, 16 p.

Burke, K., and Wilson, J. T., 1972, Is the African plate stationary?: Nature, v. 239, p. 387–390.

Calderone, G., and Butler, R. F., 1984, Paleomagnetism of Miocene volcanic rocks from southwestern Arizona: Tectonic implications: Geology, v. 12, p. 627–630.

Champion, D. E., 1980, Holocene geomagnetic secular variation in the western United States: Implications for global geomagnetic field: U.S. Geological Survey Open-File Report 80-824, 314 p.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 283–311.

Coe, R. S., 1967, Paleo-intensities of the Earth's magnetic field determined from Tertiary and Quaternary rocks: Journal of Geophysical Research, v. 72, p. 3247–3262.

Colton, H. S., 1936, The basaltic cinder cones and lava flows of the San Francisco Mountain volcanic field: Flagstaff, Arizona, Museum of Northern Arizona, 58 p.

Cooley, M. E., 1962, Geomorphology and the age of volcanic rocks in northeastern Arizona: Arizona Geological Society Digest, v. 5, p. 97–115.

Cox, A. V., Doell, R. R., and Dalrymple, G. B., 1964, Reversals of the Earth's magnetic field: Science, v. 144, p. 1537–1543.

Dalrymple, G. B., 1979, Research note: Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558–560.

Dalrymple, G. B., Silver, E. A., and Jackson, E. D., 1973, Origin of the Hawaiian Islands: American Scientist, v. 61, p. 294–308.

Damon, P. E., 1966, Correlation and chronology of ore deposits and volcanic rocks: U.S. Atomic Energy Commission Annual Progress Report C00-689-60, 46 p.

Damon, P. E., Shafiqullah, M., and Leventhal, J. S., 1974, 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 archaeology and paleoclimate. Part I, Regional studies: Flagstaff, Arizona, Geological Society of America, Rocky Mountain Section Meeting (Northern Arizona University), p. 221–235.

Doell, R. R., and Cox, A., 1965, Measurement of the remnant magnetization of igneous rocks: U.S. Geological Survey Bulletin 1203-A, p. 1–32.

Duncan, R. A., and McDougall, I., 1976, Linear volcanism in French Polynesia: Journal of Volcanological and Geothermal Research, v. 1, p. 197–227.

Eastwood, R. L., 1974, Cenozoic volcanism and tectonism of the southern Colorado Plateau, *in* Geology of northern Arizona with notes on archaeology and paleoclimate. Part I, Regional studies: Flagstaff, Arizona, Geological Society of America, Rocky Mountain Section Meeting (Northern Arizona University), p. 236–256.

Eaton, G. P., Christiansen, R. L., Iyer, H. M., Mabey, D. R., Blank, H. R., Jr., Zietz, I., and Gettings, M. E., 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787–796.

Everson, J. E., 1979, Regional variations in the lead isotopic characteristics of late Cenozoic basalts from the southwestern United States [Ph.D. thesis]: Pasadena, California, California Institute of Technology, 454 p.

Holm, R. F., 1984, Growth and development of San Francisco Mountain, a composite volcano in northern Arizona: Geological Society of America Abstracts with Programs, v. 16, p. 224.

Jackson, E. D., Silver, E. A., and Dalrymple, G. B., 1972, Hawaiian-Emperor chain and its relation to Cenozoic circumpacific tectonics: Geological Society of America Bulletin, v. 83, p. 601–617.

Laughlin, A. W., 1976, Late Cenozoic volcanism along the Jemez zone of New Mexico and Arizona: Geological Society of America Abstracts with Programs, v. 8, p. 598.

Lipman, P. W., 1980, Cenozoic volcanism in the western United States: Implications for continental tectonics, *in* Burchfiel, B. C., Oliver, J. E., and Silver, L. T., eds., Studies in geophysics: Continental tectonics: Washington, D.C., National Academy of Science (National Research Council), p. 161–174.

Loughlin, W. D., 1983, The hydrologic controls on water quality, ground water circulation, and collapse breccia pipe formation in the western part of the Black Mesa hydrologic basin, Coconino County, Arizona [M.S. thesis]: Laramie, Wyoming, University of Wyoming, 117 p.

Lucchitta, I., and Suneson, N., 1983, Mid- and late-Cenozoic extensional tectonism near the Colorado Plateau boundary in west-central Arizona: Geological Society of America Abstracts with Programs, v. 15, p. 405.

Luedke, R. G., and Smith, R. L., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-A.

MacLeod, N. S., Walker, G. W., and McKee, E. H., 1976, Geothermal significance of eastward increase in age of upper Cenozoic rhyolitic domes in southeastern Oregon, *in* Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, Proceedings, Volume 1: Washington, D.C., U.S. Government Printing Office, p. 465–474.

Mankinen, E. A., and Dalrymple, G. B., 1979, Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P.: Journal of Geophysical Research, v. 84, p. 615–626.

McKee, E. H., Smith, R. L., and Shaw, H. R., 1974, Preliminary geothermal exploration San Francisco volcanic field, northern Arizona: Geological Society of America Abstracts with Programs, v. 6, p. 458.

Minster, J. B., and Jordan, T. H., 1978, Present-day plate motions: Journal of Geophysical Research, v. 83, p. 5331–5354.

Minster, J. B., Jordan, T. H., Molnar, P., and Haines, E., 1974, Numerical modelling of instantaneous plate tectonics: Royal Astronomical Society Geophysical Journal, v. 36, p. 541–576.

Moore, R. B., Wolfe, E. W., and Ulrich, G. E., 1976, Volcanic rocks of the eastern and northern parts of the San Francisco volcanic field, Arizona: U.S. Geological Survey Journal of Research, v. 4, p. 549–560.

Morgan, W. J., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, p. 203–213.

Robinson, H. H., 1913, The San Franciscan volcanic field, Arizona: U.S. Geological Survey Professional Paper 76, 213 p.

Sass, J. H., Stone, C., and Bills, D. J., 1982, Shallow subsurface temperatures and some estimates of heat flow from the Colorado Plateau of northeastern Arizona: U.S. Geological Survey Open-File Report 82-994, 112 p.

Sauck, W. A., and Sumner, J. S., 1970, Residual aeromagnetic map of Arizona: Tucson, Arizona, University of Arizona, Department of Geosciences.

Scott, R. B., Nesbitt, R. W., Dasch, E. J., and Armstrong, R. L., 1971, A strontium isotope evolution model for Cenozoic magma genesis, eastern Great Basin, U.S.A.: Bulletin Volcanologique, v. 35, p. 1–26.

Shaw, H. R., 1969, Rheology of basalt in the melting range: Journal of Petrology, v. 10, p. 510–535.

——— 1973, Mantle convection and volcanic periodicity in the Pacific: Evidence from Hawaii: Geological Society of America Bulletin, v. 84, p. 1505–1526.

Shoemaker, E. M., Squires, R. L., and Abrams, M. J., 1978, Bright Angel and Mesa Butte fault systems of northern Arizona, *in* Smith, R. B., and Eaton, G. P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 341–368.

Smith, R. B., Shuey, R. T., Friedline, R. O., Otis, R. M., and Alley, L. B., 1974, Yellowstone hot spot: New magnetic and seismic evidence: Geology, v. 2, p. 451–455.

Smith, R. L., and Luedke, R. G., 1984, Potentially active volcanic lineaments and loci in western conterminous United States, *in* Geophysics Study Committee, ed., Explosive volcanism: Inception, evolution, and hazards: Washington, D.C., National Academy Press, p. 47–66.

Smith, R. L., and Shaw, H. R., 1975, Igneous-related geothermal systems, *in* White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States—1975: U.S. Geological Survey Circular 726, p. 58–83.

Stauber, D. A., 1982, Two-dimensional compressional wave velocity structure under San Francisco volcanic field, Arizona, from teleseismic P residual measurements: Journal of Geophysical Research, v. 87, p. 5451–5459.

Stewart, J. H., Moore, W. J., and Zietz, I., 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geological Society of America Bulletin, v. 88, p. 67–77.

Strangway, D. W., McMahon, B. E., and Larson, E. E., 1968, Magnetic paleointensity studies on a Recent basalt from Flagstaff, Arizona: Journal of Geophysical Research, v. 73, p. 7031–7037.

Thompson, G. A., and Zoback, M. L., 1979, Regional geophysics of the Colorado Plateau, *in* McGetchin, T. R., and Merrill, R. B., eds., Plateau uplift: Mode and mechanism: Tectonophysics, v. 61, p. 149–181.

Ulrich, G. E., and Nealey, L. D., 1976, Structural and eruptive patterns in the San Francisco volcanic field, northern Arizona: Geological Society of America Abstracts with Programs, v. 8, p. 641–642.

Warner, L. A., 1978, The Colorado Lineament: A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, p. 161–171.

Wenrich-Verbeek, K. J., 1979, The petrogenesis and trace-element geochemistry of intermediate lavas from Humphreys Peak, San Francisco volcanic field, Arizona: Tectonophysics, v. 61, p. 103–129.

Wolfe, E. W., Ulrich, G. E., and Moore, R. B., 1983, San Francisco volcanic field, Arizona: Volcano News, no. 13, p. 1–3.

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