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1994, pp. 147-164. https://doi.org/10.56577/FFC-45.147

in:

Mogollon Slope (West-Central New Mexico and East-Central Arizona), Chamberlin, R. M.; Kues, B. S.; Cather, S. M.; Barker, J. M.; McIntosh, W. C.; [eds.], New Mexico Geological Society 45 th Annual Fall Field Conference Guidebook, 335 p. https://doi.org/10.56577/FFC-45

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VOLCANOES AND NEOTECTONIC CHARACTERISTICS OF THE SPRINGERVILLE VOLCANIC FIELD, ARIZONA

L. S. CRUMPLER[1], JAYNE C. AUBELE[1] and C. D. CONDIT[2]

[1]Department of Geological Sciences, Brown University, Providence, RI 02912; [2]Department of Geology/Geography, University of Massachusetts, Amherst, MA 01003

Abstract—The Plio-Pleistocene Springerville volcanic field (SVF) is one of the largest basaltic volcanic fields in the western U.S.. It is petrologically and volcanologically diverse and includes tholeiitic, alkalic and evolved alkalic rock types characterized by a general evolutionary trend in petrology in which tholeiitic rocks account for 24% of the field volume and were erupted early, and alkalic and evolved alkalic rocks (hawaiite, mugearite, and benmoreite) were erupted later. The average volume rate of effusion over the history of the field (1.5 X 10^{-4} km^3/a) is similar to rates observed for other cinder-cone type volcanic fields throughout the world, but lower by about an order of magnitude than typical rates associated with large volcanic edifices and calderas. The magma supply in the Springerville volcanic field was long-lived, but too low and sporadic to sustain a single large volcano. Large-scale physiographic and morphologic features in the Springerville volcanic field reflect the kinematics of on-going, weak late Cenozoic, distributed tectonic deformations. The style, distribution and geometry of individual eruptions record the influence of contemporaneous tectonic stresses on the ascent and emplacement of magmas as well as environmental conditions present at the time of the eruptions. The general absence of strong patterns of fissure vents appears to be a consequence of the absence of regional tensile strain. Neotectonic structures are interpreted to indicate that left lateral shear stresses in the brittle crust occurred throughout much of the history of the Springerville volcanic field, rather than simple tensile stresses that would result in long fissures. Deeply penetrating faults in the northeast edge of the field interrupted the deep regional ground water flow and contributed to formation of spring deposits (travertine) in the northern margin of the field. The neotectonic deformation appears to record a transtensional style of lithospheric extension across this part of the southern margin of the Colorado Plateau in response to continued late Cenozoic clockwise rotation of the Colorado Plateau.

INTRODUCTION

The Springerville volcanic field is an areally extensive late Pliocene to Pleistocene basaltic volcanic field in east-central Arizona and western New Mexico, lying on the inboard edge of the Colorado Plateau and along the easternmost Arizona segment of the Mogollon Rim. It is the southernmost of the predominantly basaltic, late Cenozoic volcanic fields located around the margin of the Colorado Plateau (Figs. 1,2) and one of the largest basaltic cinder cone-type volcanic fields in the western United States. It is also one of the best characterized in the detail of geologic mapping, chemical sampling, and absolute and relative age determinations (Condit et al., 1994). The combination of large size and relative youth of the volcanism means that a great number of individual vents and diverse styles of basaltic volcanism and vent morphologies are present, representing a natural museum of physical volcanological characteristics exposed in one setting. For these reasons, the Springerville field represents an excellent opportunity to understand the characteristics and origin of cinder cone fields.

In this study, following a brief review of general characteristics of the field, we discuss some salient volcanological features not generally included in previously published accounts of the petrology, lithology and chronology of the Springerville field. Our purpose is to characterize features of general interest in understanding the regional physiography, their relationship to the origin of the individual volcanoes, and the insight they provide into the characteristics and origin of the cinder cone field style of volcanism.

OVERVIEW OF THE FIELD

The Springerville volcanic field was one of the last large basaltic volcanic fields in the U.S. to be geologically mapped in detail. Ironically, it was also the first such field to be visited by Europeans in what is now the United States, as it is likely that Coronado passed through the center of the field in 1540 on his journey northward to Zuni Pueblo and the Rio Grande (Bolton, 1974). Aside from a passing mention by Darton (1915), who first noted its volcanic origin, (and the mention of its cones and lava flows in the opening setting of one of Edgar Rice Burroughs's (1935) John Carter of Mars books!) almost nothing was known about the volcanology of the field until it was mapped by us a decade ago. Earlier geologic mapping studies in the region (e.g., Sirrine, 1958) were concerned primarily with the surrounding sedimentary rocks and with the ground water geology. Previous work on volcanic rocks in the region (Merrill and Péwé, 1977) focused primarily on White Mountain Baldy to the south, a series of mainly porphyritic trachytic rocks 5 to 6 Ma older than most of the Springerville volcanic field rocks and now exposed as a deeply dissected shield-shaped volcano (Nealey, 1989). Because of differences in age, style of volcanism and overall preservation of the two areas, we refer to the younger region of basaltic cinder cones and flows (mostly north of highway 260) as the Springerville volcanic field in order to distinguish it from the older White Mountain Baldy complex. Most local residents and vacationers from Phoenix, however, still refer to the elevated and forested region in eastern Arizona as a whole as the White Mountains, including the youthful part of the field between Show Low, Concho, Springerville, Eagar, Greer and Pine Top that is the focus of this study.

The Springerville volcanic field (SVF) is a prominent topographic feature in the southern Colorado Plateau. From Interstate Highway 40, near the entrance to Petrified Forest National Park or south of Holbrook, the SVF appears on the horizon to the south as a broad, bumpy domical rise. From the town of Springerville the view of the eastern one-third of the field presents a profile of numerous clustered cinder cones along a broad slope (Fig. 3). Some of the domical relief of the field may be attributed to volcanic construction, as the total thickness of volcanic rocks based on water well logs is estimated to average in excess of 90 m in the central northern parts of the field (near Vernon) and up to 300 m in regions of highest vent density. But the presence of pre-volcanic sedimentary outcrops at high elevations within the central field also suggests that the elevation of pre-existing surfaces contributed to the total relief. The substrate beneath much of the SVF consists of gently dipping Mesozoic sediments, including the Triassic Petrified Forest Formation of the Chinle Group on the north margin, and coarse alluvial gravels of Tertiary age. Similar alluvial gravels also occur throughout the Mogollon Rim.

The SVF covers an area of 3000 km^2 and is notable for its cinder cone field style, large volume of lava flows, and petrologic diversity (Aubele and Crumpler, 1983; Condit et al., 1989 a,b; Crumpler et al., 1990; Cooper et al., 1990; Connor et al., 1992). The field consists

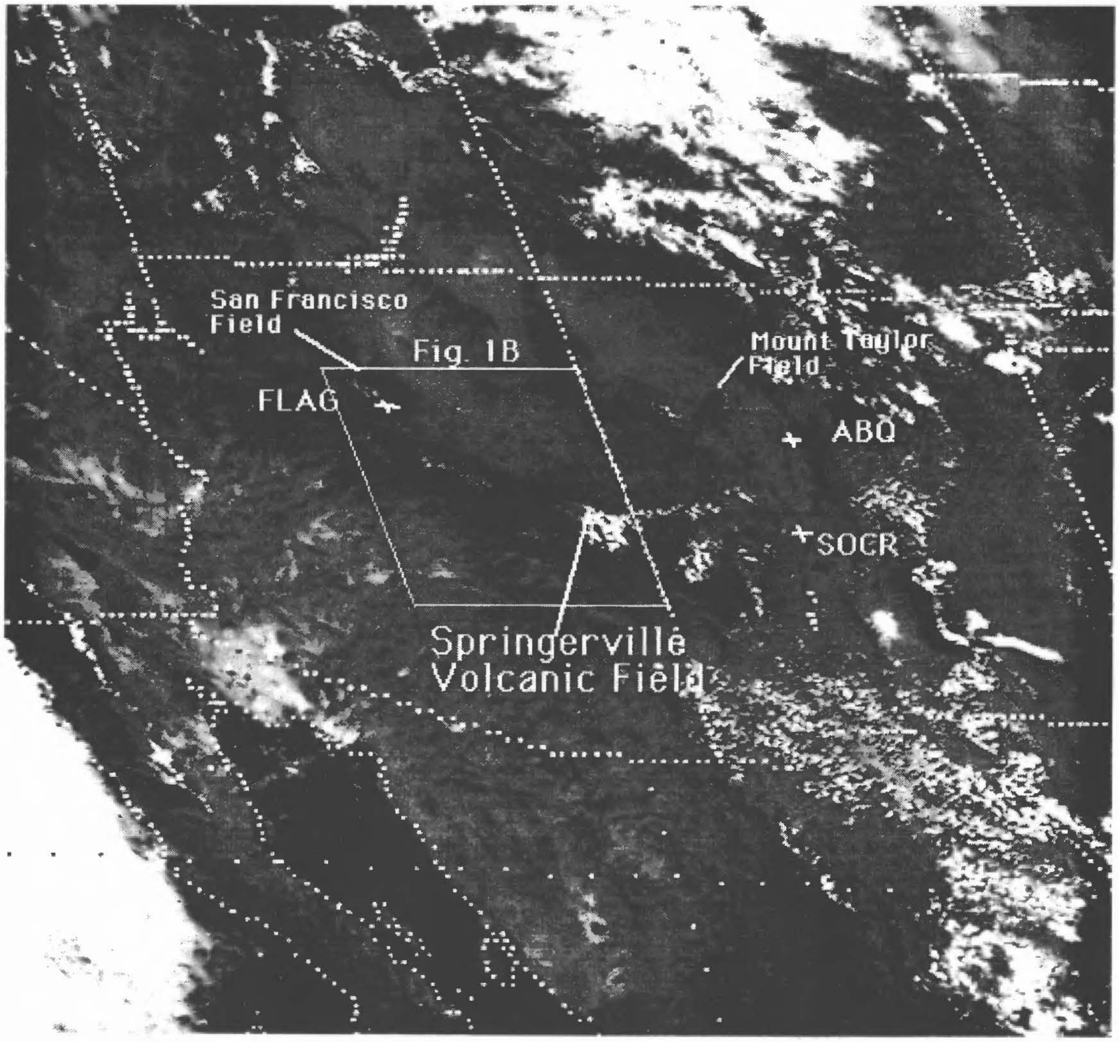

FIGURE 1. Satellite view of the Southwestern United States (GOES satellite image). The Mogollon Rim appears as a dark elongated area in central Arizona. Several prominent late Cenozoic volcanic fields are clearly visible around the margins of the Colorado Plateau. Rectangle outlines the area shown in Fig.2.

primarily of basaltic lava flows, related basaltic pyroclastic cones up to several hundred meters in relief, and isolated more differentiated extrusive rocks. Although cinder cones and their flows occur throughout the western U.S., fields with the large dimension and morphological diversity of the SVF are relatively uncommon. In overall areal extent, and in volcanic and petrologic style, the Springerville volcanic field is comparable to the San Francisco volcanic field (Ulrich et al., 1989) near Flagstaff and the Mount Taylor field in western New Mexico (Crumpler, 1982,1990).

Unlike the San Francisco or Mount Taylor fields, however, the SVF does not include a topographically dominating large volcano or volcanic complex of equivalent age. Nonetheless, elevations in the field exceed 3000 m at the base of Greens Peak (Fig. 4), a moderately young cinder cone that lies at the summit of the field and attains a summit elevation of 3140 m, from which there is a view of most of the surrounding region of closely-spaced cinder cones. The upper elevations within the field are characterized by aspen, spruce and open grassy parks supported by frequent summer rainfall. In the extreme northern end of the field, near the town of St. Johns, elevations are less than 1830 m and the landscape is characterized by rolling grasslands, junipers, and related semi-arid and transition zone vegetation.

Run off and spring discharge from the higher elevations feed the two major drainages in the field, the Little Colorado River, which originates near Greer, and the North Fork of the White River, in the central part of the field. The Little Colorado skirts the eastern edge of the field, along which there are numerous paleo-Indian sites, such as the Casa Malpais site near the town of Springerville, and continues northward into the interior of the Colorado Plateau. During the course of mapping, many sites within the field were identified that preserve pre-historic as well as historic artifacts.

Over 400 individual volcanic vents were identified during the course of our mapping at a scale of 1:24,000 and compiled at a scale of 1:100,000 (Condit et al., 1987; Aubele et al., 1987; Condit et al., 1989; Condit et al., 1994). Vents include cinder cones, maars, viscous domes, a laccolith or cryptodome, related lava flows and various pyroclastic deposits. Neotectonic faults and folds (Fig. 5) were also identified by detailed geologic mapping. Identification and characterization of the basic lithologic units and tectonic deformation were constrained through chemical analyses of 257 lava flows, trace element analyses, and petrogenetic modeling, 30 K-Ar age dates, and extensive paleomagnetic determinations. Radiometric ages of volcanic rocks range mostly from ~0.3 to 3 Ma (Condit et al., 1994), only a few of which are older than 2.5 Ma. Ages of individual units not dated were constrained on the basis of combining the existing K-Ar dates (Laughlin et al.,1979; Laughlin et al.,1980; Aubele and Crumpler, 1983; Condit and Shafiqullah, 1985; Aubele et al., 1986; Cooper et al., 1990) and magnetic polarity reversal records from 90 units with detailed stratigraphic relationships determined through mapping of every flow unit.

The chemical data demonstrate that the field is petrologically diverse and includes tholeiitic, alkalic, transitional alkalic-tholeiitic

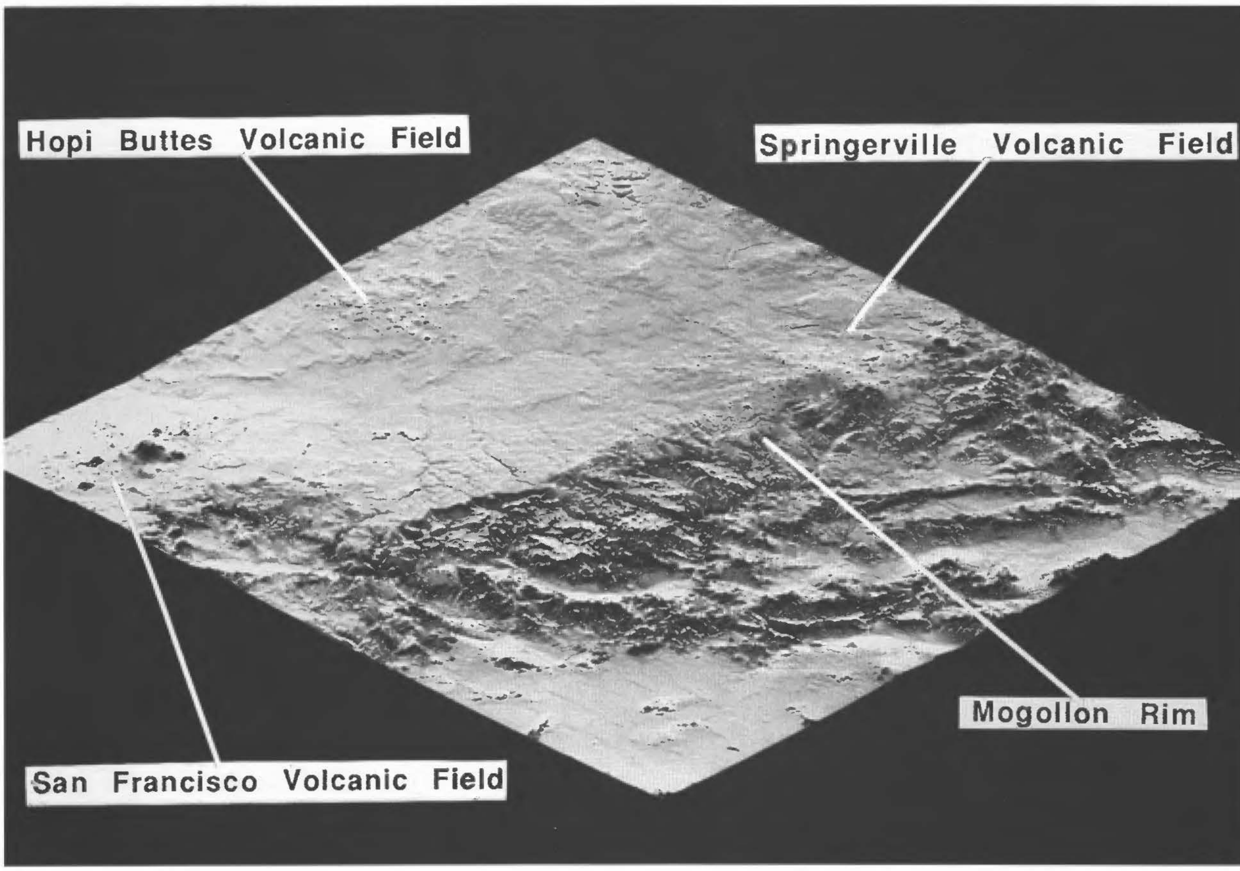

FIGURE 2. Oblique digital elevation model centered on the south and southwest margin of the Colorado Plateau. The large-scale relief across the Mogollon Rim and Transition Zone is clearly visible, as is the small scale relief associated with the San Francisco, Springerville and Hopi Buttes volcanic fields. North is toward the upper left corner.

and evolved alkalic rock types (hawaiite, mugearite and benmoreite). Tholeiitic rocks account for 24% of the field volume and were erupted early, whereas alkalic and evolved alkalic rocks were erupted later (Fig. 6). Most of the older tholeiitic rocks occur as extensive sheets exposed mostly in the northern periphery of the field and now form extensive low grasslands. The source vents for these flows are largely unexposed and probably lie buried to the south under the stack of younger alkalic lavas. Consideration of the total number of vents, the volume of volcanic rocks, and the duration of volcanism indicates that the average volume rate of effusion over the history of the field was 1.5×10^{-4} km^3/a (Crumpler et al., 1990). Because the volumes and ages are well-constrained by detailed mapping, we are able to estimate effusion rates from several intervals in the history of the field. These suggest rapid onset of nominal effusion rates and steady production of magmas for at least 2 Ma (Fig.7). The average recurrence interval between individual eruptions was on the order of 3000 years.

The geometric center of active vents migrated toward the east at a rate of approximately 2.9 cm/yr, such that the older vents tend to lie on the west side of the field and the youngest occur on the east side, in an area to the north and west of the town of Springerville (Condit et al.,1989a). A similar pattern of generally eastward migration of successive eruptions was noted in the San Francisco volcanic field near Flagstaff (Tanaka et al.,1986). Because the vector representing this drift in the center of activity corresponds roughly with the motion of the North American continent, it is possible that this eastward drift in volcanism reflects relative motion between the lithosphere and a fixed sublithospheric source region for most of the basaltic melts. The nature of the stationary mantle source is undetermined, but need not represent a sublithospheric plume. Other origins might include viscous heating of

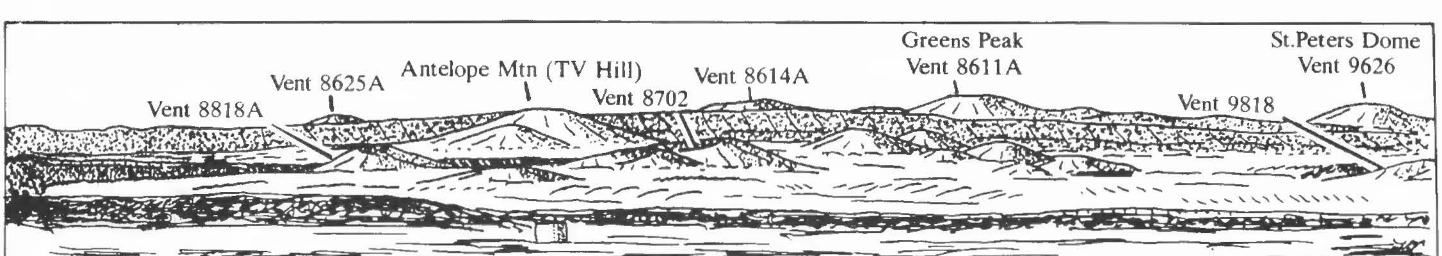

FIGURE 3. Sketch of the western skyline from the town of Springerville, showing the southern and eastern one-half of the Springerville volcanic field. The cinder cones along the top of the skyline all lie at greater than 2700 m above sea level. Vent numbers and names of some prominent cinder cones are indicated. Saint Peters Dome is dated at 0.67± 0.02 Ma and Greens Peak is dated at 0.76±0.02 Ma. Most lava flows in the nearer slopes of the field are about 1.5 Ma. The cultivated alluvial plain of the Little Colorado River and Round Valley (Springerville-Eagar) lies in the foreground. Sketch by LSC.

FIGURE 4. Greens Peak (viewed from SE) a typical cinder cone of intermediate age, lies at the topographic summit of the field. One of the longer lava flows in the field erupted from this cone and flowed to the northwest.

a lithospheric bump or keel (Condit et al., 1989a), viscous heating of a sublithospheric upwarp intruding the base of the lithosphere along the Jemez lineament, progressive eastward propagation of sublithospheric fractures opened during clockwise rotation of the Colorado Plateau (Spence and Gross, 1990), or melting of sublithospheric mantle inhomogeneities (Jemez lineament) in the presence of regional increased heat flow.

NEOTECTONIC STRUCTURES

Detailed mapping has allowed us to identify structural features, many of which appear to offset the basaltic lavas dated between 0.9 and 1.3 Ma and thus appear to be relatively young (Fig. 5) (Aubele et al.,1986; Crumpler et al.,1989). Neotectonic features are described here first because they relate to discussions of many of the individual volcanic features. These structural characteristics are also of interest because they are evidence for the kinematics of ongoing weak, late Cenozoic, distributed tectonic deformation along this part of the Mogollon Rim. Only the more prominent structural elements are described here. The overall sense of deformation is one of limited, very nearly incipient strike-slip faulting along several regional fault zones striking northwest through the field, in which strike-slip appears to be accommodated by normal faulting near the ends of the fault zones.

Tectonic deformation within the SVF is expressed at several scales, including regional topography, local faulting and folding of basalt flows, and vent alignments and clustering. The tectonic tilting of basalt flows as young as those in the SVF is relatively unusual in our experience, but is well constrained. Many of these characteristics are subtle and some are detected only as a result of apparent back-tilting of the substrate on which individual basalts have flowed. Tectonic tilting of flows is readily distinguished from primary variations in surface slope of flows, based on a knowledge of the source direction, consideration of the path taken by the flow over original topography, and thickness of the flow in relation to apparent tectonic relief on the substrate. In short,

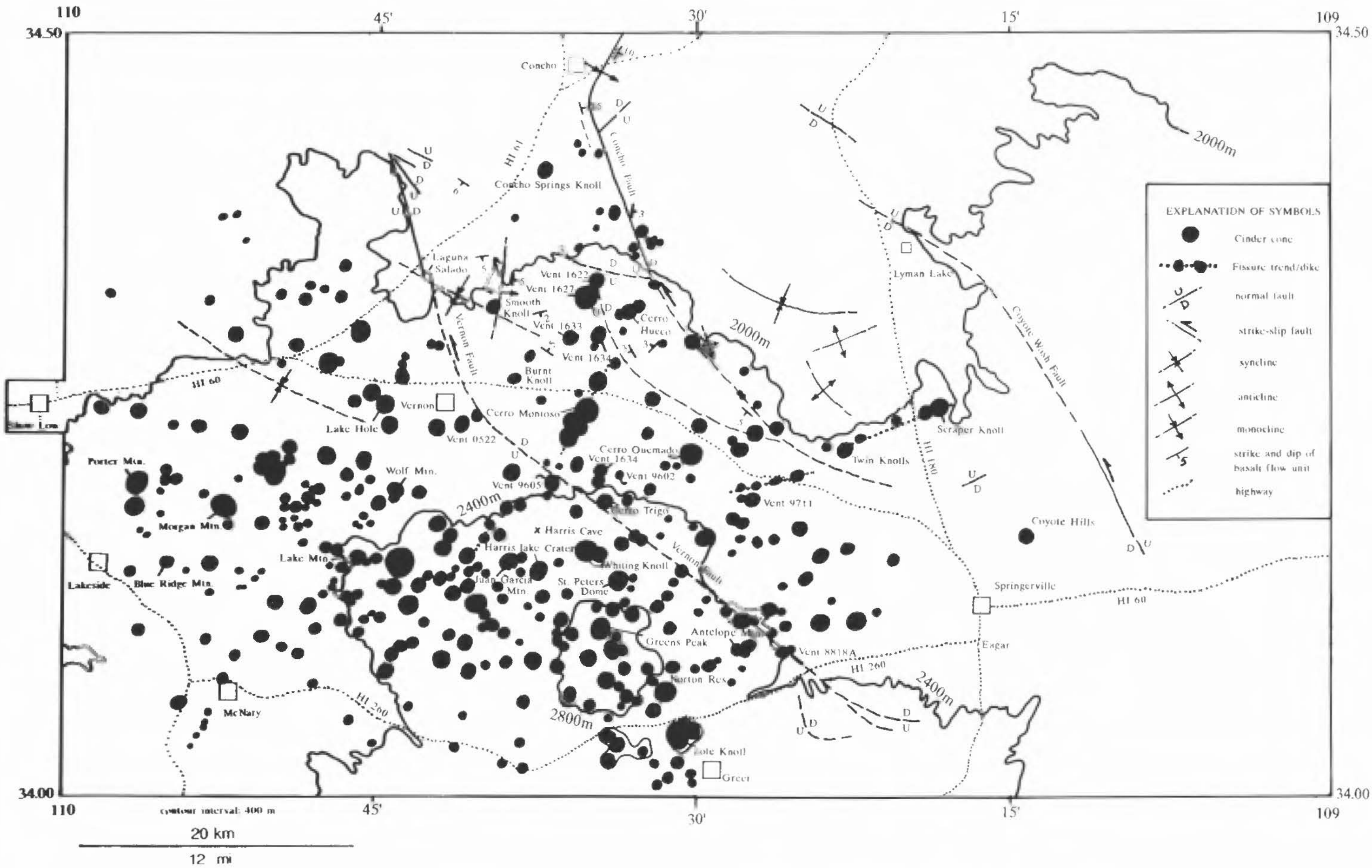

FIGURE 5. Map of the Springerville volcanic field showing the locations of all cinder cones and related vents, neotectonic features, and regional topography of the field. For the corresponding detailed lithologic, geochemical, chronological and paleomagnetic maps of the Springerville volcanic field refer to Condit et al., 1994. [Editor's note: Normal faults with an indicated component of strike slip are more appropriately labeled as oblique-slip faults.]

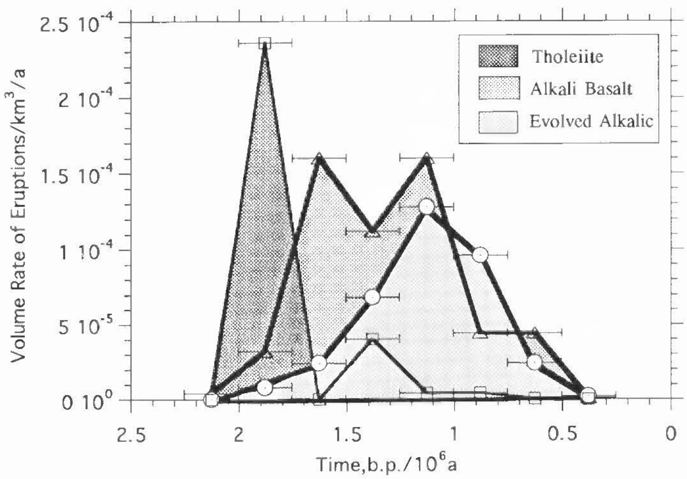

FIGURE 6. Volume rates of eruption of tholeiites, alkali olivine basalts, and evolved alkalic rocks with time. Although the three types erupted contemporaneously, there is a trend toward more evolved alkalic compositions and slightly decreased volume rates of eruption with time.

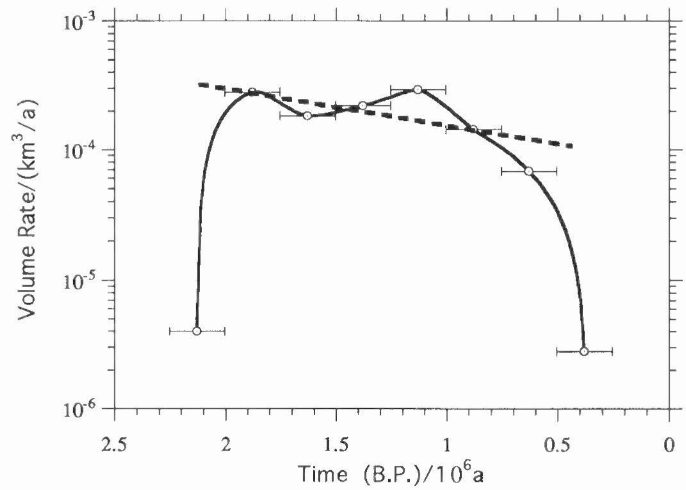

FIGURE 7. Total volume rates of eruption for all rock types in the Springerville field as a function of time. Oblique line is least squares fit to the peak activity period during which volume rates of eruption were on the order of 10^{-4} km^3/a. This is typical of the rates for cinder cone fields in general. Based on data in Condit et al.(1989a).

many basalt flows appear to have "flowed up hill" or over swells that exceed the thickness of the individual flows and have clearly been deformed subsequent to their emplacement.

Three principal deformation zones

Three principal deformation zones are defined by major topographic steps across the field, with a variety of smaller scale structural features (Fig. 5). The topographic steps include the Vernon fault zone striking northwest across the center of the field; the Concho fault zone, which is approximately parallel to the Vernon fault and extends from the eastern margin to the northern margin of the field; and the Coyote Wash fault zone, which lies mostly on the eastern margin of the field and also strikes northwest. Between these major fault zones are a number of smaller faults that splay out from the main deformation zones. Other isolated features include synclines, anticlines and a few short fissure vent trends.

Topographically the Vernon and Concho fault zones correspond to prominent down-to-the-northeast steps or scarps and the Coyote Wash fault zone is characterized by a down-to-the-southwest scarp (Fig. 8). Each of these appear at some point along their length to be related to faulting or folding of either pre-existing surfaces or the later volcanic units. Throughout much of the length of these steps, many of the of the basalt flows appear to have flowed over the steps, and the steps might otherwise be interpreted at first sight as simple pre-existing erosional scarps. Although it is likely that erosion has been important in enhancing segments of the scarps, local deformation features at various points along their length (including graben, normal faults, apparent strike-slip deformation, and pull-apart basins), imply that the scarps are fundamentally structural in origin. This varied and complex style of deformation is not consistent with an origin of the scarps through simple normal faulting and a significant component of strike slip is inferred as discussed below.

Vernon fault

The most prominent step occurs as a scarp trending from the vicinity of Greer on the southeast to Vernon, and is here referred to as the Vernon fault (Fig. 5). The southeastern end of the Vernon fault zone splays into a series of east-west trending normal faults forming high scarps in the much older (~ 6 Ma) basalts from the White Mountain Baldy complex in the vicinity of Greer. Immediately northward, within the younger Springerville basalts, the fault zone is expressed only as a slight rise in the surface between vent 8818A and Antelope Mountain (Fig. 3). Farther northwestward along the Vernon fault zone there is little direct evidence for structural control because of the dense forest cover and abundance of cinder cones. Instead, deformation along the center of this scarp is characterized by anomalous outcrops of pre-volcanic sediments and ridge-like remnants of earlier volcanic units oriented along the apparent structural trend and around which later basalts have flowed. However, at Vernon the scarp-like character disappears and the trend changes to a more northerly direction. Along this northerly trend are several structural features with observable offsets. The presence of an apparent pull-apart basin, Laguna Salado (located north of the town of Vernon and 1 km east of Highway 81) (Fig. 9), is consistent with the accommodation of small amounts of left lateral simple shear strike-slip motion. At its terminus, several kilometers northwestward, the Vernon fault appears to be accommodated by a series of straight normal faults and graben that displace older basalt units (Fig. 9; see also Fig. 5). These faults are oblique to the strike of the Vernon fault zone and are consistent with an origin as extensional Riedel fractures associated with the left-lateral shear.

Concho fault

The Concho fault zone occurs along the next prominent topographic step to the north and is characterized by an arcuate trend of discontinuous structural features from an area beginning near the junction of Highway 60 and Highway 180-666, approximately 5 km west of Springerville and traversing northwest across the field to the town of Concho. In addition to its association with a topographic step, the Concho fault zone also marks the northeastward limit of most vents in the field and therefore appears to exert an indirect control on the location of vents. Throughout the length of the Concho fault zone are numerous fault scarps, graben and local anticlinal folds that displace basalt units. On the southeast end the Concho fault is little more than a low scarp-like rise. But farther northwest, near the center of the northern field, are a series of fault scarps with normal fault displacements, basalt benches with surfaces tilted several degrees, and a gentle anticline approximately 1 km long and oriented obliquely to the lineament. At a point northwest of Cerro Hueco along the Concho fault a complex anastomosing series of arcuate fractures cuts the surface of a long ridge of older basalt for about a kilometer. Farther northwest and a few kilometers southeast of Concho the structural trend widens into a deep graben along which basalt units and a cinder cone appear to have been down dropped 30 m. The south flank of the graben consists of a series of step-like fault scarps and steeply dipping basalt flow units. Farther northwest, along the south wall of the graben, basalt units are cut by a deep wash and dip steeply into the graben (Fig. 10; see also Fig. 4). All

FIGURE 8. Oblique view to the north-northwest of the central field, centered on Highway 60 west of Cerro Quemado. Several cinder cones are visible. The large scale relief of the field is characterized by prominent topographic steps related to major structural trends. Two of the major topographic steps cross the upper half of the image from lower right to upper left and are annotated by dotted lines. The arrow points in the direction of the regional gradient and indicates the apparent sense of deformation and displacement of the surface. Aerial photo by C. Condit.

of the volcanic units deformed at this graben are at least 0.7 Ma old, but the fact that the slopes of the graben are affected very little by erosion is evidence that the faulting is considerably younger. Northward of the deep wash and along the same fault trend, the Concho fault abruptly terminates and merges with a northeastward-striking monoclinal fold. Old basalts capping a mesa east of Concho dip gently to the southeast along the west side of the mesa. The sense of deformation in many of the structures along the length of the Concho fault zone, their occurrence along a narrow belt of deformation, and the overall kinematics of the large scale structures associated with it are interpreted to be the results of oblique slip involving a slight amount of left lateral strike slip and down-to-the-northeast normal faulting. In general, normal faulting is more prominent along the southern extremities of the fault and apparent strike-slip movement appears to be dominant along the central portion of the fault zone. The mergence of the Concho fault at a right angle with a monocline suggests that in this case the proposed left-lateral strike-slip was accommodated by shortening at its northern terminus. Although no marker units or piercing points occur that would confirm strike slip or its absolute displacement, the disparate types of deformation and the relatively confined belt along which they occur is similar to deformation associated with known strike-slip faults (Sylvester, 1988).

Coyote Wash fault

The Coyote Wash fault, on the east and northeast side of the field (Fig. 5), is similar in many structural characteristics to the Concho and Vernon faults, but is curved in an opposite sense and with an opposing (down to the southwest) topographic step and component of normal faulting. The detailed structural character of this fault zone is poorly constrained compared with other fault zones in the field due to the extensive development of drainages throughout much of its southern segment, but normal fault displacements of at least 10 m are visible in sandstone outcrops east of the Coyote Hills. Relatively minor monoclinal features (not shown in Fig. 5) appear to splay to the east from this fault before the fault becomes obscured to the south. Together, the Coyote Wash fault and the Concho fault thus enclose a structural depression in the northeast quadrant of the field best described as a larger scale version of the Laguna Salado pull-apart basin. Within the structural depression, a series of anticlinal and synclinal folds in the basalts are randomly oriented, suggesting contractional strain throughout the depression. In addition, several examples of other recent anticlinal and synclinal warping of basalt surfaces are generally consistent with secondary strain patterns associated with these major deformation trends.

East of the SVF, young basalts and their vents in the Red Hill area of New Mexico (Crumpler and Aubele, 1990) appear to be cut by numerous parallel, northeast-striking normal faults. Thus, the Springerville field appears to occur at a distinct junction in tectonic trends bound on the east by northeast-striking faults and characterized throughout most of the field by northwest-striking major fault patterns.

Origin of regional deformation

The southeastern termini of the Concho and Vernon faults appear to be the sites of normal faulting or fissure vents and imply that the apparent tectonic transport to the northwest along both major structural trends is accommodated in part by extensional strain at their southeastern ends. In this sense the regional deformation is altogether similar to thin-skinned or listric-style shallow faulting, typical of some areas of

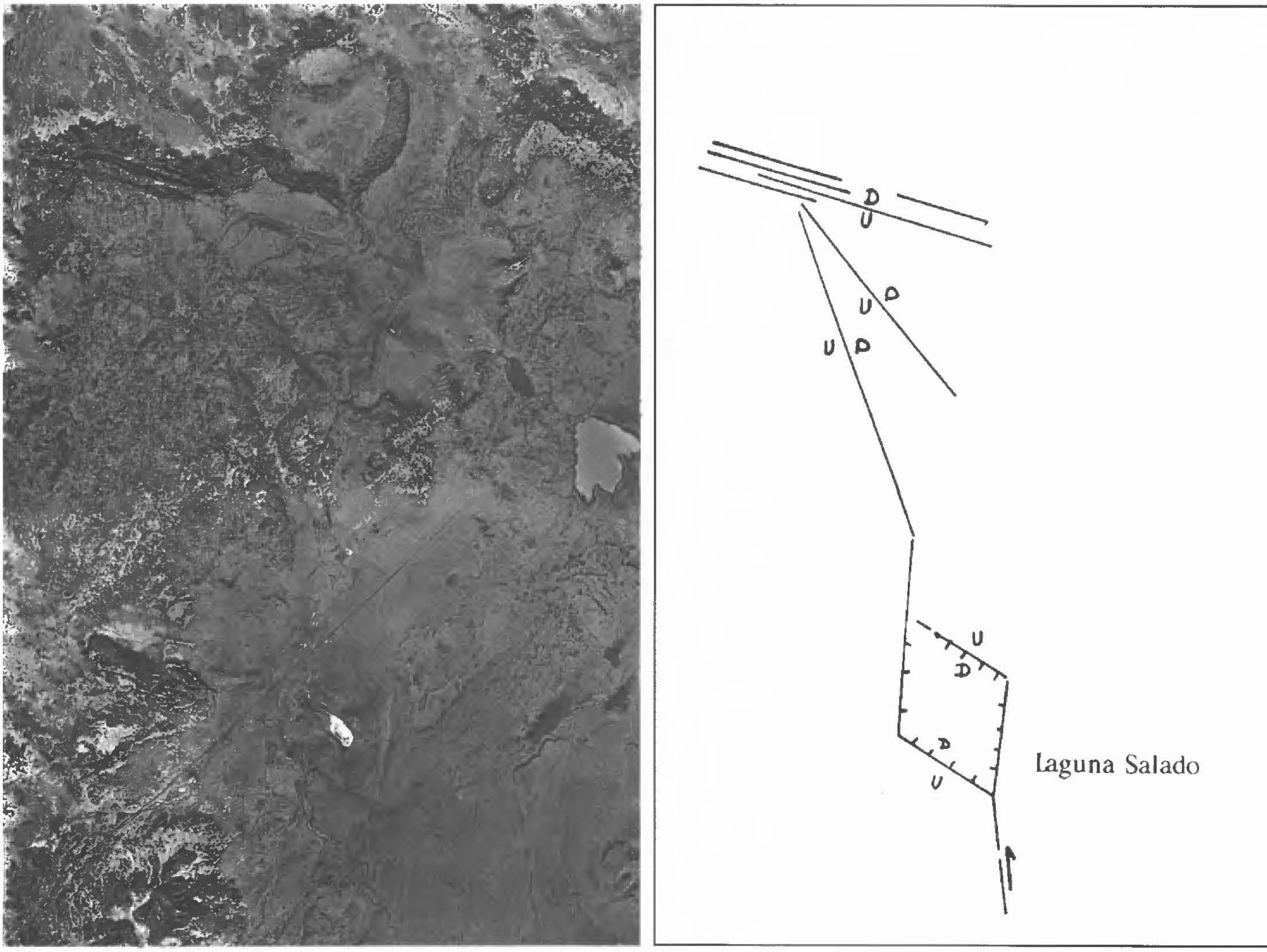

FIGURE 9. Air photo and sketch map showing a series of normal faults and graben accommodating left lateral simple shear along the Vernon fault zone trending northwest through the center of the image. A large pull-apart basin (Laguna Salado) is visible along the fault zone in the lower half of the image. Width of image (E-W) is 10 km.

the Basin and Range, and is headed at simple breakaway zones on the south. The regional tectonic stresses associated with the margin of the Colorado Plateau are likely to be complex because of the combined effects of Basin and Range deformation, the influence of the opening of the Rio Grande rift, and structural fabrics remaining from the Laramide history of the Mogollon Rim. However, relatively simple tectonic transport can account for most of the neotectonic deformation in the SVF. Northeast-southwest extension along the Mogollon Rim could account for the stepped faulting in the SVF, but slight amounts of left-lateral strike-slip better account for the diversity and style of observed structures. Although the northeast-southwest extension might reflect continued extension and encroachment of the Basin and Range on the Colorado Plateau (Brumbaugh, 1987), strike-slip faulting is not widely observed in the Colorado Plateau and the possible origin of proposed left-lateral shear strain is unclear. Strike-slip could arise in this region if large scale clockwise rotation of the Colorado Plateau has occurred as suggested by numerous authors (Steiner, 1986; Hamilton, 1987; Spence and Gross, 1990; Bryan and Gordon, 1990). Some structural elements of the Jemez lineament, the Colorado Plateau and the Rio Grande rift have been attributed to this sense of motion (Spence and Gross, 1990). Although the regional left lateral shear of the magnitude

FIGURE 10. Tectonically tilted basalt unit (approximately 1 Ma) near Concho, dipping steeply toward the alluvial-filled floor of a graben that forms part of the Concho fault zone.

and orientation predicted by clockwise rotation of the Colorado Plateau about the pole established by Bryan and Gordon (1990) in northern New Mexico is consistent with the observed orientation and sense of tectonic transport observed in the SVF (Fig. 11), the presence of this sense of tectonic transport must be considered controversial, as this sense of motion does not account for many elements of the structure in the Rio Grande rift on the eastern margin of the Colorado Plateau (e.g., Kelley, 1982). Deformation in relatively young basalts of the SVF is nonetheless evidence that at least small amounts of rotation of the Colorado Plateau might have contributed to the observed deformation over the past 2 Ma, irrespective of the additional tectonic influences that may have governed principal deformations outside the plateau and in the Rio Grande rift.

Regardless of the origin of the regional structure, there is evidence that can be interpreted as left-lateral strike-slip type deformation and a regional pull-apart basin style of regional deformation. It may be relevant to the origin of the field as a whole that the center of vent concentrations is offset from the center of the overall pull-apart style depression that characterizes the regional structure.

DESCRIPTION OF INDIVIDUAL VOLCANIC FEATURES

In the following, many of the more interesting and unusual physical volcanological characteristics of the field are discussed. Detailed discussions of petrology, chemistry and age relations may be found in Condit et al. (1989; 1994). The emphasis here is on physical features of general interest, but illustrates that the record of basaltic volcanism is of more than geochemical interest and may provide useful insights into the physical processes of the emplacement of cinder cone fields, the ascent and eruption of basaltic magmas, the influence of regional tectonics on eruption characteristics, and the regional geology.

Because many vents and their associated volcanic features are unnamed, we have assigned "vent numbers" to each volcanic center and refer to vent number frequently. Vent numbers are shorthand for location referenced to the township, range and section in which the vent occurs; the first digits of the township and range are omitted because they are repetitive throughout the field. Multiple vents within a single section are arbitrarily assigned sequential letters of the alphabet. Thus, vent 0621 is located in sec 21, T10N, R26E.

Lava flows

Most of the field volume consists of lava flows. The pyroclastic materials associated with cinder cones account for only about 10% of the total volume of the volcanic field, as is the case for the few volcanic fields for which estimates of the relative volumes of lava and pyroclastic materials have been made (Wood, 1980; Hasenaka and Carmichael, 1985). Cinder cones are prominent topographically and record the conditions of eruption, but most of the magma erupted was emplaced as lava flows. Dimension, thickness, volume, shape, response to slopes, state of preservation and source vents for individual flows are constraints for conditions of magma ascent and eruption. Characteristics of lava flows that are of general interest include exposures of primary lava flow morphology, lava tubes and flows of unusual dimensions, morphology and petrology.

Youngest lava flows

The youngest flows in the SVF are transitional basalt with moderately abundant olivine phenocrysts, erupted from the Twin Knolls (vents 0833 and 0828), two overlapping, dark, morphologically youthful cinder cones 8 km NW of the town of Springerville, along the abandoned old Highway 180-666 to St. Johns (Fig. 12). The northern cone is also somewhat more eroded and has grass-covered slopes. The primary morphology of the lava flows is of the *aa* type. Two flows of slightly different age were erupted. The older of the two flowed northward down local drainages developed in earlier basalts toward the Little Colorado River and is exposed approximately 10 km north of Springerville along the west side of Highway 180; the highway crosses the flow near its terminus about 11 km north of Springerville. The surface of this lava flow is locally overlain by alluvium and outcrops of the actual aa surface are weathered slightly reddish-brown, but pressure ridges and related larger-scale structures associated with young lava flows are preserved. Samples from a road cut in this flow yielded an

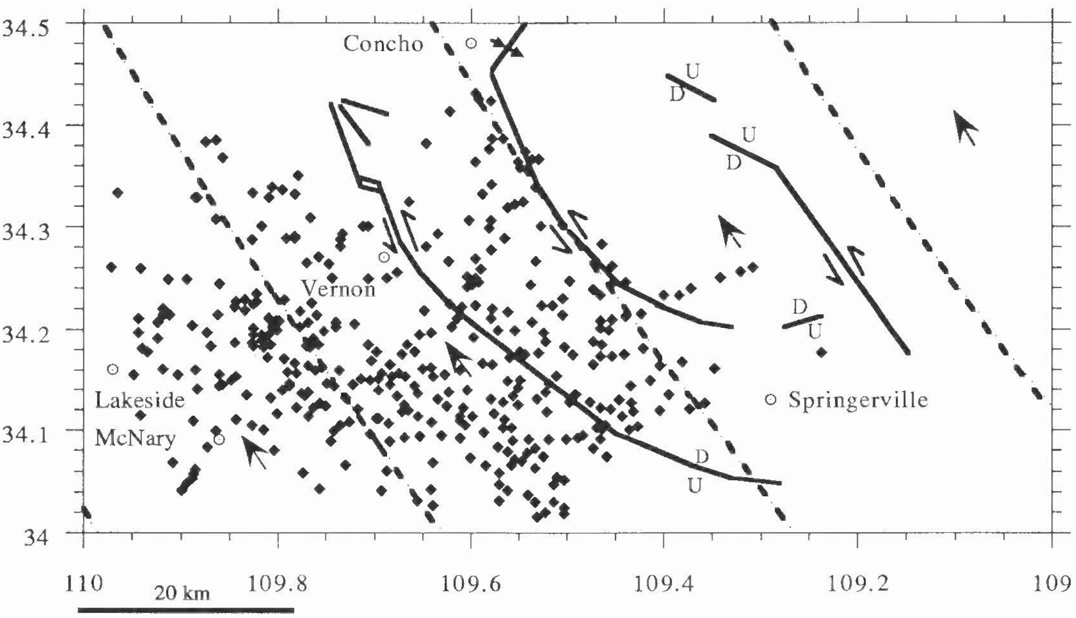

FIGURE 11. Map illustrating the location and orientation of the main faults in the Springerville volcanic field (dashed lines) in relation to small circles (lines of latitude shown by dashed lines) about the suggested (Steiner, 1986) pole of rotation (37°N latitude and 103°W longitude) for the Colorado Plateau. Arrows indicate the local sense of plateau motion with respect to the continental U.S.. Most faulting in the SVF is consistent with small amounts of left-lateral simple shear oriented parallel to the suggested rotation of the Colorado Plateau. The implied sense of rotation is consistent with many characteristics of structure within the Colorado Plateau (Spence and Gross, 1990), although some characteristics, such as the late structure of the Rio Grande rift (Kelley, 1982), are not clearly related to this sense of motion. Note that the center of the structural basin in the northeast is offset from the center of concentration of vents. Offset of most of the faulting from the center of the field suggests that the Springerville volcanic field may have resisted the northwestward translation of the rest of the Colorado Plateau and resulted in the opening of a large pull-apart basin in the Lyman Lake region between Springerville and St. Johns.

age of 0.75±0.13 Ma (Laughlin et al., 1980). A younger, petrographically similar, and morphologically better preserved flow was erupted from the southern of the two overlapping cones and spread out at the base of the cone. This flow is dated at 0.308±0.070 Ma. This appears to be a case where two eruptions, greatly removed in time, occurred from very nearly the same vent area. Although cinder cones are often considered to be "monogenetic", several studies of other cinder cones in the southwest (Renault et al., 1988; Wells et al., 1990) have shown that repeated eruptions over geologically extended periods of time from a single cone may be more common than previously thought.

These young vents must lie at the trailing end of the observed record of activity in the field. However, considering that these eruptions occurred several hundred thousand years ago and that the mean interval between eruptions for the field as a whole is approximately 3000 years, they may not represent the final eruptions. Activity of the SVF may have shifted further east, as a morphologically youthful eruption dated at 0.071± 0.012 Ma (McIntosh and Cather, this guidebook) occurred further east in the Red Hill area (Crumpler and Aubele, 1990) of western New Mexico.

Other young flows, slightly more eroded than the older of the two Twin Knolls flows, occur in the vicinity of Cerro Hueco (vent 1626A; see discussion of maars below), in the north central part of the field (Fig.11). Although no age is available for these flows, they are more degraded than the Twin Knolls flows, yet display more primary morphologic features than flows dated at about 1 Ma. This intermediate age, based on morphology, agrees with the estimated age determined strictly from stratigraphic and paleomagnetic data (0.30-0.79 Ma) (Condit et al., 1994).

Lava ponds

Two thick flow units of a slightly older flow (0.70-0.97 Ma) in the Cerro Hueco area are mugearitic in composition and were erupted from a relatively youthful-appearing cone (vent 1622) about 2 km west of Cerro Hueco. The upper of the two flow units was erupted from a deep breach in the cone and is unusual in two respects. First, scattered about the surface of this flow are small mounds of horizontally to slightly-dipping cinder and spatter up to 10 m in relief (Fig.13). The fact that the internal bedding in each of these mounds appear to be truncated around the margins, together with the unusually large breach in the source cone, suggests that the mounds are large fragments of the cone rafted away from the flank during the final phases of the eruption. Rafted cone fragments are common on lava flows erupted from cinder cones (Holm, 1987), because of the difference in density of cinders versus lava flows and the relatively low shear strength of pyroclastic cones.

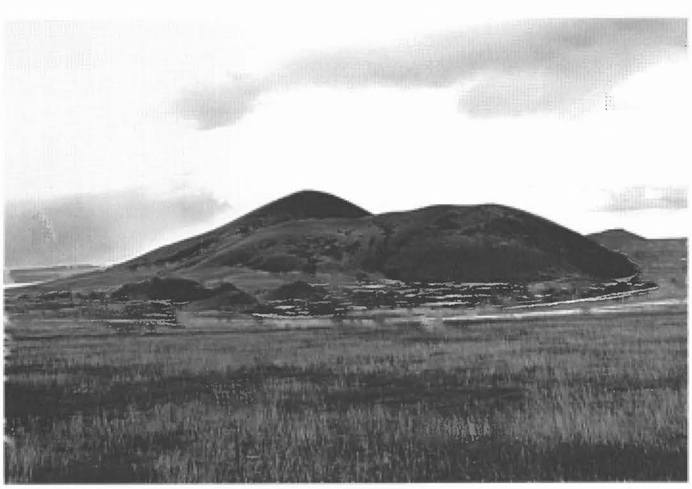

FIGURE 12. Twin Knolls viewed from the SW. Only the youngest of the two cinder cones northwest of the town of Springerville is visible. This is the site of the youngest dated eruptions within the field (0.75±0.13 Ma and 0.308±0.070 Ma). The southern of the two cones was emplaced on the south exterior flank of the northern cone and appears to be several hundred thousand years younger.

The second unusual characteristic of this flow is its overall shape and relief. The flow is unusually thick, short and equant in plan view; in fact, it is similar in morphology to more viscous lavas. An even more unusual characteristic is the overall concave surface relief, forming a broad closed depression in the center of the flow that extends out to the flow margins, broken only by the isolated rafted cone fragments. Petrographically, the margins are characterized by unusually large olivine phenocrysts, whereas the interior basin is aphyric. It is chemically similar to many of the transitional-to-evolved basalts throughout the field. This morphology might represent a perched lava pond or an inflated lava flow. Ponding in lava flows is common where a sudden decrease in slope causes a flow to spread laterally, increases the area relative to the volume of lava, results in rapid cooling relative to channelized lava flows, and as a result increases the yield strength relative to that of basaltic lavas on steeper slopes. Observation of actively forming lava ponds in Hawaii (Wilson and Parfitt, 1993) showed that the effusion rate can be estimated based on the observed dimensions of the pond. Employing their method, and using the observed dimension (1.8 km pond diameter and a slope of 1.5° determined for the surface of the underlying flow unit) we estimate a rate of effusion of 3.4 m^3/sec. This may be categorized as being between average and low for most historic basaltic eruptions, so there appears to have been nothing unusual about the rate of emplacement. The relatively low, but steady rates of eruption might also have favored lava inflation, subsequently followed by draining and sagging of the lava surface.

At least three other examples of near-vent lava ponds of similar dimension and petrographic character (porphyritic margins and aphyric interiors) occur in the field, associated with vents 1633 (dated at 1.19±0.04 Ma, Aubele et al., 1986), 1634 and 9711. Vent 1622 and these three examples all occur within a narrow corridor oriented west-northwest along one of the prominent topographic steps that trend through the field. A potentially related fact is that all four flows are unusually porphyritic, although of different petrographies and whole rock chemical content. And in each case the ponded flow appears to have erupted onto the surface of an earlier flow unit, thus implying that topographic ponding in a pre-existing valley was unlikely. The unusual number and proximity of such flows, and their occurrence along one of the principal tectonic deformation zones in the field, might imply that unusual conditions of magma ascent influenced by regional tectonism were responsible for their occurrence over a restricted area. Two of the cinder cones from which these lava flows were erupted are among only a few vents in the field that are characterized by bipolar fusiform bombs and spindle bombs, an indication of relatively mild strombolian activity compared to the more fragmental characteristics of the pyroclastic deposits associated with most of the vents in the SVF. This implies that the volatile overpressures characteristic of vigorous vesiculation associated with most eruptions were relatively lower in the case of these flows and that the non-hydrostatic, possibly tectonic, component of the driving pressure may have been more significant. Alternatively, the abundant phenocrysts characterizing the margins of the flows might reflect a purging of a crystal-rich crustal magma reservoir followed by more aphyric lavas later. The high phenocryst content of initial lavas would tend to increase the bulk yield strength of the margins, whereas later aphyric and low yield strength lavas would accumulate and pond within the interior. Why the scenario should be repeated several times in this region is unclear, but it is possible that unusual conditions of tectonic over pressure induced in the mid-to-shallow crustal reservoirs during contemporaneous (oblique-slip?) faulting may have led to unusual driving pressure characteristics.

Longest lava flow/lava tube

One of the longest of the younger lava flows is an aphyric basalt of transitional petrologic type erupted from the topographic summit of the field (Greens Peak, vent 8611A). This flow traveled 18 km north-northwest, where the terminus is within sight of Highway 60 and 1.6 km west of Burnt Knoll (vent 0512).The margin of the Greens Peak flow is unusual in that it is relatively digitate and complex in outline compared with many flows in the field and includes many short subsidiary

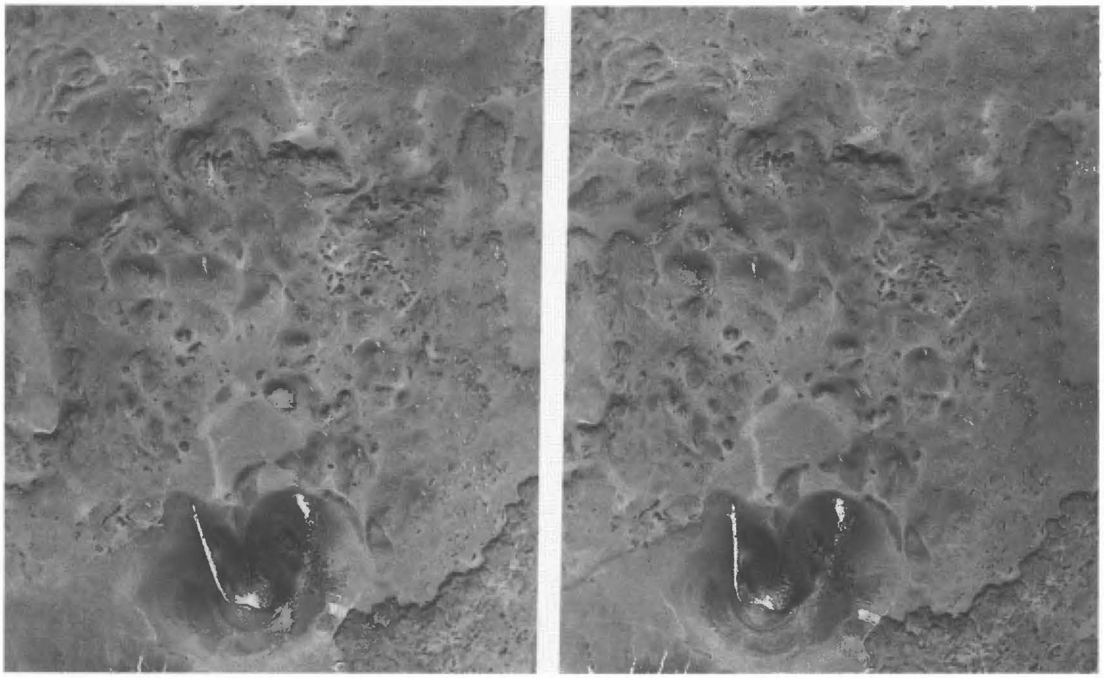

FIGURE 13. Stereo air photo pair of the ponded flow of vent 1622 west of Cerro Hueco. Hummocks distributed throughout the flow are interpreted to be rafted cone fragments torn from the main cone during formation of the large northward-facing breach in the crater. Several similar ponded flows occur throughout this part of the field. Image width is 2.5 km.

tongues and "break outs". One of the few lava tubes in the field occurs in the Greens Peak flow and the emplacement of the flow through lava tubes likely accounts for its relatively great length rather than an unusual composition or eruption dynamics. In addition, the unusual shape is consistent with tube-fed emplacement of the flow, as numerous "breakouts" and short flow pods are generally enhanced in flows emplaced by lava tubes (Taylor, 1992). The only identified opening to the lava tubes of the Greens Peak flow (Harris Cave) occurs south of the fire road connecting Vernon and the Whiting homestead (at the base of Cerro Trigo) and is 200 m west and 300 m south of where the road crosses Mineral Creek (SE 1/4 NE 1/4sec. 18, T9N, R6E). This flow is dated at 0.76±0.02 Ma (Cooper et al., 1990) (See Fig. 5 for location.) Prehistoric Indian artifacts removed from this tube by two local residents when they were children are on display in the regional museum in St. Johns.

Ultramafic nodules and megacrysts

Basalt flows and vents bearing ultramafic nodules are rare in the SVF compared with other fields around the Colorado Plateau. At the west end of Lake Boynton and just east of Negro Knoll (vent 9605), a variety of small nodules occur in an exposure near the terminus of an alkali olivine basalt flow (estimated 0.73-0.90 Ma) erupted from Whiting Knoll (vent 9621 and 9622). Smaller xenoliths also occur in the hawaiitic basalts from the Harris Lake crater vent area (vent 9630 or 9525B). Kaersutite megacrysts up to 1 and 2 cm in size also occur in the margins of a flow from vent 9603 exposed west of Cerro Trigo (in SW1/4 NW1/4 sec.4, T9N, R6E). Throughout the field, a variety of crystal-rich and megacrystic lava flows occur and are identified in unit description comment on the lithologic map (Condit et al., 1994).

Cinder cones and related vents

Cinder cones are visually arresting but constitute a small volume of the volcanic materials in the field. The general characteristics of cinder cones are remarkably similar over a wide range of settings (Kear, 1957; Colton, 1967; Porter, 1972; Wood, 1979; Hasenaka and Carmichael, 1985). In detail there are variations in morphology and these differences are important because they are frequently records of the different conditions under which each magma batch was erupted (McGetchin et al., 1974; Head and Wilson, 1989). In addition, the pattern of vent distributions and associated dikes may also be indicators of regional stress orientations and the structural controls on volcanism (Wadge and Cross, 1988).

Large scale patterns associated with fissures or dikes are relatively rare in the Springerville field (Fig. 5), but vents in the SVF are not randomly distributed. Distinct clusters, local complexes and non-fissure alignments are detected on the basis of quantitative cluster and lineament analysis (Connor et al., 1992). The highest concentration of vents (8-12 vents/100 km^2) occurs in the south-central part of the field in a corridor extending approximately from Lake Mountain on the west to Greens Peak on the east. A lower density complex extends from a cone cluster at Cerro Montoso to the vicinity of Cerro Hueco in the north-central part of the field. Connor et al. (1992) also showed that several quantitatively significant linear arrangements occur, the most prominent striking northwest, north-northeast and east-northeast. A lesser trend strikes north and east-west. Only two of these correspond to the few known fissure orientations (northeast and east-northeast). These trends define a radially-oriented pattern with respect to the center of the field, and we conclude that although the alignments are not true fissures, they might represent zones along which selective ascent and mid-crustal storage of magmas occurred along pre-existing regional structural grains. The dominant northwesterly cone alignment direction, for example, is similar to identified orientations (Fig. 5) of the more prominent anticlines and synclines. It is possible that the regional left-lateral strain interpreted from observations resulted in a relatively weak, vertically-oriented, less principal stress orientation and no single orientation was favored for true fissure eruptions. True fissures occur near the sites of pure normal faulting at the southern end of the Concho fault, or associated with fractures, interpreted as Riedel structures, in the vicinity of the major deformation trends.

Fissure vents

Because conditions of magma emplacement in the brittle upper crust imply ascent of magmas in dikes of large length with respect to their width, the initial interaction of dikes with the surface initiate most eruptions as fissures. Evidence for fissure vents is rarely seen in the SVF and implies that the length of typical fissure vents must be less than 1 km (the average diameter of the cinder cones), such that most of the initial fissures, if present, are buried by the later construction of vents. Only three prominent fissure trend lines are known to occur, and all are in regions where there is neotectonic evidence for extensional strain or where shearing strain is predicted from kinematic relations to be at a minimum relative to much of the field. Several of the fissures appear to be truncated or step left across the main fault zones in the field and are further evidence for the influence of the proposed fault zones on stress in the brittle crust throughout the region. As the driving pressures necessary to open dikes of differing length and widths in different strain environments may be calculated (Reiches and Fink, 1988), these observations ultimately may prove useful as a method of inferring the magnitude and orientation of regional tectonic stresses occurring at the time of eruption.

Character of pyroclastic materials

Many of the cinder cones consist of a variety of pyroclastic deposits, fluidal agglomerate, bombs, spatter and clinkery cinder. The more spectacular fluid types of pyroclastic deposits, such as ribbon and spindle bombs, appear to be unusually rare in the SVF compared to other basaltic fields around the Colorado Plateau. Instead, most of the Springerville cones consist of loosely-welded cinder and local clinkery agglomerate. This type of cone might develop if the fire fountains associated with eruptions forming the Springerville cones were generally more dispersed, a probable consequence of increased volatile content, vesiculation and disruption of the magmas. Gas-rich eruptions are capable of generating smaller particle sizes due to the increased fragmentation of the magma during terminal phases of ascent in the conduit. The resulting particles may be rapidly cooled below the solidus before falling to the surface of the cones such that little actual welding or formation of rootless flows occurs. Interaction of the magmas with regional water tables, especially during the past 2 million years when climates were frequently wetter in this region and aquifers were more productive may be one reason for increased incorporation of volatiles in eruptions. There is no evidence that the compositions of the magmas were themselves unusual or likely to be associated with unusual amounts of volatiles.

Young cinder cones

Varied states of preservation of primary volcanic morphologies occur in the SVF cinder cones. Unbreached craters typical of many youthful cones, however, are relatively rare. Prominent unbreached cones include Lake Mountain (vent 9423), Juan Garcia Mountain (vent 9525) and Cerro Montoso (vent 0621). The summit crater of Cerro Montoso, a prominent cinder cone in the center of the field on Highway 60 (32 km west of Springerville), is 50 m deep from rim to floor.

The southern of the two vents forming the Twin Knolls (vent 0833), the youngest center in the field (Fig. 12; see discussion of lava flows above), is characterized by dark red to black cinders, flank slopes that are at or near the angle of repose for loose cinder, and only the initial stages of erosional incision. The dark color of the cinders contrasts with most of the cones in the field, which are weathered, partially soil covered, and light reddish brown in color. Most of the cones in the SVF are slightly eroded, such that their flank slopes are less than the angle of repose typical of active cinder cones (30 ± 5°), and cut by radial drainages, as typified by Cerro Trigo (vent 9610). The cinder cones of the SVF are grass covered at elevations below 2440 m, or covered above this elevation by dense stands of aspen, ponderosa pines, or spruce, particularly on their northern flanks. Because of the latter condition, exposures of cinder cone structure are best observed at lower elevations. Scraper Knoll (vent 0919B), 2.4 km east of Highway 180 and 8 km north of Springerville (Figure 14A), is a typical example of the general state of preservation of the cones in the SVF. Based on this example, the slopes of the typical Springerville cinder cone may be divided into several elements (Fig. 14B), which correlate with different states of erosion on the upper flanks and deposition of the eroded materials on the lower flanks. Erosion has resulted in gradual reduction of the slopes relative to the angle of repose of cinders, creating an angular truncation of the bedding planes in the upper one-half of the cone flank in which the cinder and ash layers dip more steeply down slope than the surface topographic slope (Fig. 14C). As a result, the bedding planes are exposed and may be discerned as faint concentric bands around the upper flanks. The lower flanks are correspondingly buried by alluvial cinders and soils that contribute to an apron of debris that gradually diminishes in slope and blends with the more or less horizontal surface of the surrounding landscape. The slope angle is slightly less in the upper flank where the bedding planes are close to horizontal. This suggests that material is removed by erosion and transported down the cone flank from the area of exposed nearly horizontal bedding planes more rapidly than within the steeply dipping sections, and that once material is deposited in the apron it is more resistant to further

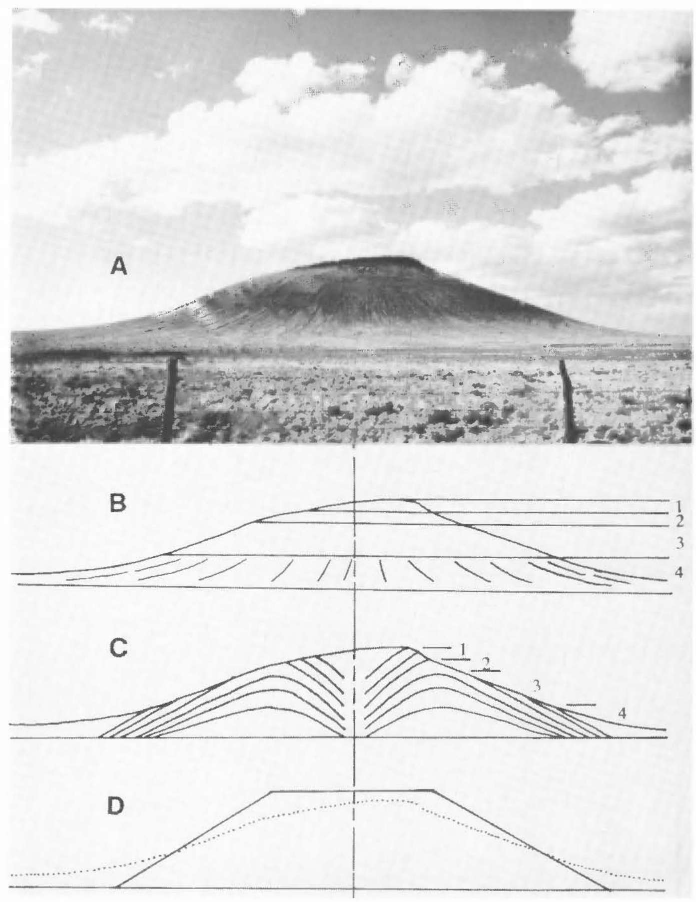

FIGURE 14. A, View of Scraper Knoll (vent 0919B) from the south. This cinder cone is typical of the state of preservation of the cinder cones of intermediate age in the Springerville volcanic field. B, Sketch map showing divisions of the flanks of Scraper Knoll defined on the basis of apparent local dip of cinder bedding planes and overall texture and color of the slopes: (1) inward-dipping, welded, near-vent cinder, spatter, and agglomerate; (2) cinder and spatter layers characterized by nearly horizontal bedding orientation; (3) outward dipping fine cinders; and (4) erosional debris apron. C, Interpretation of the relationship between erosion, secondary surface characteristics of the cone, and primary internal structure illustrating the influence of internal structure on patterns of erosion. D, Reconstruction of the original profile of Scraper Knoll compared with current profile. Reconstruction is based on assumption of an initial outer slope of ~29° (based on the average angle of repose of ash and cinder throughout the field) passing through the current contact between the encircling alluvial fan and current dissected flanks of the cone.

transport. As a consequence, there is a slight reduction of slope in the upper flank relative to lower flanks. This characteristic control of internal structure by erosion might also account for the rounded or domical profile of older cinder cones instead of a butte-like summit surrounded by a lower-sloped debris apron.

The summit rim of Scraper Knoll is not gently rounded and illustrates why many cinder cones in the SVF, and in fields of similar age throughout the Southwest, often appear morphologically more youthful to the untrained eye than they actually are. On most cinder cones at the stage of erosion in Scraper Knoll, and in slightly eroded recent cones elsewhere throughout the world, ash and spatter beds near the upper flanks dip toward the original vent crater and, together with the more strongly welded near-vent characteristic of pyroclastic materials near the summit, result in more resistant erosional behavior of the near-summit slopes. As a result, prominent outcrops of inwardly-dipping agglomerate, spatter and cinder typically occur around the uppermost flanks and summit. These "spatter rims" or "ramparts" define the rim of a type of structural crater in many cases, which mimics the original crater-shaped summit topography of more youthful cinder cones. Exposures of these fine-grained, almost glassy, and magnetite-rich materials of spatter rims in the upper flanks of many cones are frequently preferred sites for paleomagnetic sampling. Unfortunately, the outcrop faces of spatter rims are also frequently streaked by fulgarite (silicates fused into greenish glass by lightning strikes). The strong electric fields associated with lightning strikes are known to have adverse effects on remnant magnetism even without melting. Paleomagnetic sampling of these outcrops is accomplished only with careful analysis.

Although the prominent agglomerate and spatter rims represent cones that are somewhat eroded, they appear to be relatively short-lived features that occur mostly on younger cones. At this elevation, spatter rims appear to be characteristic of cinder cones between 0.3 Ma and 0.8 Ma, as exemplified by Scraper Knoll. This morphology/age sequence is climate-dependent and only locally applicable, however, as spatter rims characterize much older cones elsewhere (for example, the Mount Taylor field; Crumpler, 1980).

Vent 1627, a symmetric and elegantly shaped basalt cone that erupted flows of porphyritic hawaiite, is notable because of the presence of specular hematite in the vent area. This occurs as coatings on cinders and bombs and in the loosely welded cinder and spatter materials exposed in an erosional breach crater in the southeast summit crater rim. Post-eruptive specular hematite mineralization is observed commonly in volcanic vents and occurs in cinder cones over a wide range of ages throughout the world (Aubele, 1979; Naboko and Glavatskikh, 1984).

In a few cinder cones, erosion has exposed the connection between surrounding flows and former lava ponds. In vent 0718 (1.1 km north of Highway 60 and 30 km west of Springerville), a hawaiite lava flow forms a ramp-like ridge that extends from a bulbous outcrop in the center of the cone to the surrounding petrologically similar basalt flows. This sequence therefore records the emergence of magma from the cone and its connection with the surrounding lava flows. This is unusual because the stratigraphic relationship between most cinder cones and their erupted lava flows is rarely visible and there is rare evidence for compositionally and petrographically similar basaltic lavas within the mass of the cones. Most basalt samples recovered from within cinder cones are typically fine-grained spatter composed dominantly of microlitic, opaque, oxides-rich, rootless flow materials.

Shield volcanoes

At least two volcanic vents in the SVF are broad, shield volcano-shaped accumulations of lava flows capped with small summit pyroclastic deposits. These include Blue Ridge Mountain (vent 9328B, estimated 1.32-1.87 Ma) on the west side of the field near Pinetop, and Coyote Hills on the east side of the field about 7 km northeast of Springerville (Fig. 15). Flows from the Coyote Hills are relatively young (0.82±0.04 Ma), as dated from the upper flow unit in an outcrop in the roadcut east of Springerville (Laughlin et al., 1980). The outlines of many of the individual flows from which the shield volcano flanks are built are still clearly visible in air photos. Several similar shield-shaped vent areas occur further east, in the area south of the Red Hill region of New Mexico.

These shield-building eruptions are of interest because they illustrate a different style of eruption from that occurring throughout much of the history of the SVF. Most vents in the field consist of cinder cones from which one to several flow units erupted, usually totaling considerably less than 0.1 km^3. In contrast, the Coyote Hills consists of numerous tongue-like flows radiating from the summit area, an indication that many small effusive eruptions were repeated from this vent over an extended interval. The overall volume of lava is not much greater than that associated with single effusions of typical cinder cones. This means that the eruption proceeded in a more "staccato" style, as compared with that associated with cinder cones. The origin of these two different styles is not clear, as there is nothing anomalous about the petrology of the shield volcanoes or the morphological style of the flows with respect to the "monogenetic" cone-type eruptions. Models of the ascent and eruption of basaltic magmas (Wilson and Head, 1983) suggest that rather than resulting from gross differences in the magmas themselves, these variations in eruption style might instead simply reflect differences in the physical characteristics of the reservoirs and ascent pathways. In cinder cones and their lava flows, typically larger volumes of magma are supplied in a few batches to the surface, accompanied by more vigorous gas exsolution. In the shield volcanoes, for multiple, small volume flow units to erupt, there must have been a repetitive behavior in the supply of small volumes of magma from the underlying reservoir, as well as relatively limited magma vesiculation and pyroclastic activity at the vent.

One non-petrologic characteristic that exerts a strong influence on magma ascent, feeder dike emplacement, and eruption style is the state of stress in the crust (e.g., Delaney et al., 1986; Reiches and Fink, 1988). Evidence of considerable variation in this factor exists in the Springerville region. Long, relatively recent, normal fault scarps and faults are common in the region east of Springerville, many of which cut relatively young volcanic rocks (e.g., Crumpler and Aubele, 1990) and reflect a different stress environment than that interpreted to exist throughout most of the SVF. The structural features west of Springerville appear to be characterized more by regional strike slip than regional normal faulting. The general influence of these different styles on eruptions are such that wide variations in feeder dike characteristics and magma driving pressures may be expected and could account for the different vent morphology at the Coyote Hills. However, this may not account for Blue Ridge Mountain and it is likely that additional factors may be significant.

Clearly, more sophisticated study of the physical characteristics of volcanic deposits, on a level with our current knowledge of their petrologic characteristics, is required to better assess the origin of such differences in eruption style. The influence of these conditions is a subject of a continuing analysis using the SVF.

Maars, viscous domes, and unusual vents

Although cinder cones dominate the population of vents in the SVF, a small number of vents reflect emplacement under unusual conditions of environment or magma composition. The following unusual volcanic centers are worthy of note because they offer insight into different styles of volcanism and evidence for the varied conditions under which magmas may be emplaced.

Maars

Craters resulting from probable phreatomagmatic eruptions, or maars, occur throughout the central part of the field and attest to wetter conditions throughout much of the Southwest during the lifetime of the SVF. The youngest maar, Cerro Hueco (vent 1626A), which appropriately is Spanish for "Hole in the Hill ", is located in the north central area (Fig. 16) and is one of the younger eruptions in the field. This is a morphologically impressive east-west elongated crater situated in the saddle between two cinder cones. Total relief from the summit of the

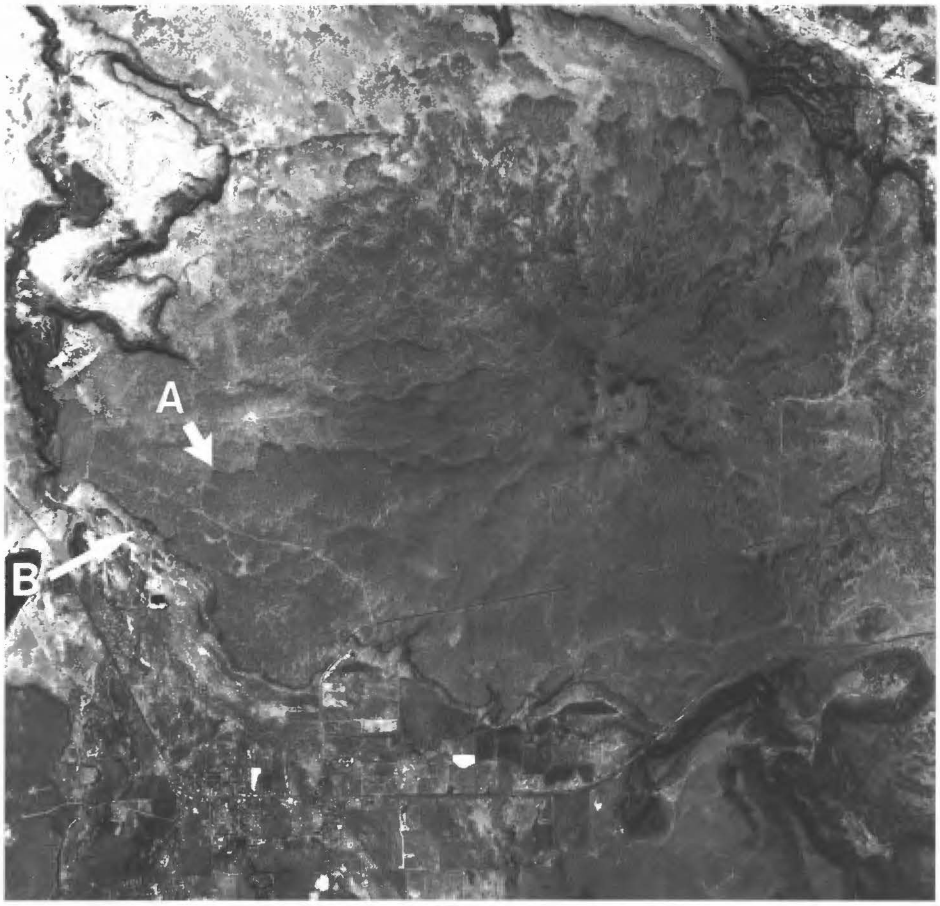

FIGURE 15. Air photo showing the Coyote Hills shield volcano and the town of Springerville (lower left) situated along Highway 60. One of the typical lava flows from which the Coyote shield volcano was built is clearly visible on the west flank (Arrow A). Arrow B indicates the Casa Malpais archeological site. Coyote Wash is in the extreme upper right. Width of image (E-W) is 11 km.

cone on the eastern rim of the maar to the bottom of the crater is 330 m; total relief from the average maar ejecta rim crest is more than 120 m. The crater was excavated through two pre-existing flow units separated by a 2-15-m-thick ash layer exposed in the the north and south crater walls (Fig. 17). The lower unit of the flow units is from a cone on the east rim, and the upper unit is from the cone on the west rim estimated to be about 0.5 Ma. Both this cone and the maar show evidence for similar minor amounts of mass wasting on their steeper slopes and may be approximately similar in age. The ejecta unit at the rim is 70 m thick and thins outward to substantially blanket surrounding lava flow surfaces for a radius of at least 1 km from the maar. The ejecta consists mostly of fine ash and cinder, but also includes accidental materials consisting commonly of blocks of basalt from the underlying flow units, less commonly of well-rounded alluvial cobbles, and rarely of angular yellow to buff-colored sandstone blocks. The cobbles are probably derived from the immediate substrate, as Tertiary conglomerates consisting of gravels and cobbles of similar lithology are exposed in the slopes of the local valley in which the maar is situated. Thus the maar-forming eruption probably originated when the Cerro Hueco magmas neared the surface and encountered the conglomerate that regional evidence suggests was likely to have been an excellent aquifer at the time of the eruption.

Several other maars are hybrid vents, the rims of which consist of interbedded palagonized tuffs and agglomerates. These probably formed in pre-existing cinder cones that subsequently erupted more phreatomagmatically. They include Harris Lake (vent 9630, estimated 0.73-0.90 Ma), Lake Hole (vent 0424, estimated 0.8-1.6 Ma; 4.8 km west of Vernon), and Smooth Knoll (vent 1526, estimated 1.15-1.45 Ma; 6.4 km N20E of Vernon). Smooth Knoll is more accurately categorized as a tuff ring, but the origin is similar in that accidental ejecta, cinders and ash, together with palagonitic materials, form a prominent crater rim around the site of former phreatomagmatic eruptions. However, in this case a subsequent cinder cone and lava pond filled in the crater. Some details of the complex intercrater stratigraphic relationships are exposed by the erosion of formerly enclosing cinders.

Accidental blocks and cinders occur on the outer flanks of Lake Hole, whereas the inner slopes consist entirely of bright reddish brown cinder and agglomerate outcrops. In this case a cinder cone was formed initially by Strombolian eruptions, but was subsequently disrupted by later, more violent phreatomagmatic activity. It is not clear whether the phreatomagmatic eruption was the ending stage of the eruption that had initially built a cone, or was an entirely later event in which magmas accidentally encountered the cone during ascent. The northeast rim of Lake Hole is considerably lower than the rest of the rim, and it appears that this side of the original cinder cone was blown away. This implies that the phreatomagmatic eruption responsible was slightly offset to the northeast from the original center of the cone. Ash and anomalously red cinder cover the pre-existing lava flows and drainages to the northeast and along Highway 60. Considering the coarse size, unusual red color typical of the interior of older cones, and unusually widespread characteristic of this ash, most of the materials likely represent cinders excavated from a pre-existing cone and blown out of the crater during the final phreatomagmatic eruption. Most ejecta may have been directed northeastward due to the location of the vent on the northeast flank of the Lake Hole cone.

Harris Lake and Norton reservoir maars are located in relatively high altitude alpine settings. The sequence of events at Harris Lake (vent 9630) is similar to that at Lake Hole; that is, a pre-existing cinder

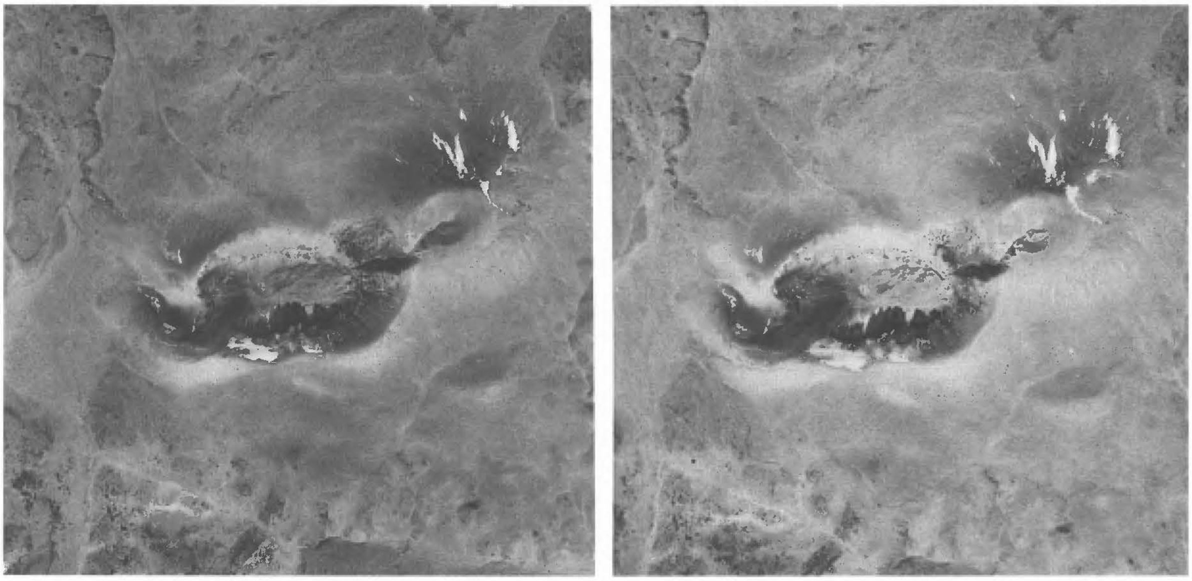

FIGURE 16. Stereo air photo pair of Cerro Hueco maar in the saddle between two cinder cones. Total relief from the summit of the eastern cinder cone to the floor of the maar is over 300 m. The cone on the west (left) end slightly predated the maar eruption and is the source of the youthful lava flow extending off the image to the northwest.

cone was partially destroyed during a final more violent phreatomagmatic eruption. Phreatomagmatic tuffs are exposed in the south rim of Harris Lake and along the outer slopes of the residual cinder cone flank forming the north rim. This sequence is likely to be governed by a balance between dike volume injection rates and ground water recharge rates. Declining volume rates and longer intervals between eruptions in later stages of the active vent history may favor increased incidents of infiltration of water into the brecciated plug of the vent area, correspondingly more violent interactions with the water table, and enhanced steam explosions. Norton Reservoir (vent 8729), located 4.9 km east of Greens Peak, is similar in many respects to the other maars in the field except that it is has a more classical maar-type morphology consisting primarily of a low circular rim of yellowish-brown pheatomagmatic tuffs surrounding a central depression.

Other maars in the SVF are generally somewhat older and more degraded. A ranch dwelling in the outskirts of Vernon, 2.4 km south and east of Highway 60 along the Vernon-McNary Road, is blithely situated in the center of what remains of a maar (vent 0522, estimated 0.91-1.53 Ma), the southern rim of which has been removed by a through-going wash and later filled with younger basalt flows. Well data indicate basalt fills the floor to a depth of at least 90 m. The prevalence of maars in the Vernon area may be attributed to the presence of well-developed drainages fed by streams from higher altitudes in this part of the field.

Viscous domes

Vents formed from eruptions of more evolved and viscous magmas are rare and in this respect the SVF is unusual, especially considering the long history and relatively great volume of volcanic rocks erupted. Eruptions of more evolved magmatic composition are common in many of the volcanic fields around the Colorado Plateau. However, at least two examples of the extrusion of more viscous flows are identified in the SVF. One striking example is Wolf Mountain (vent 9507), dated at 1.56±0.05 Ma (Aubele et al., 1986), approximately 8 km S45°W of Vernon. Here, a dome, 1 km in diameter and consisting of viscous and massive flows of porphyritic benmoreite, was emplaced on the south side of a pre-existing cinder cone that had previously erupted relatively aphyric mugearite flows. Judging from the structure and location of the dome, it erupted from a vent slightly offset from the center of the pre-existing cone. This dome is relatively degraded, with excellent exposures of massive, inward-dipping benmoreite.

A similar, although not as well exposed, occurrence of viscous benmoreite is exposed in the north flank of Pole Knoll (vent 8732, dated at 1.30±0.04 Ma, Cooper et al., 1990), a large composite cinder cone 9 km S45°E of Greens Peak (1.4 km south and 18 km west of Eagar on Highway 260). The small exposure of gray benmoreite in the north flank contrasts strikingly with the darker aphyric and olivine basalts from the main mass of Pole Knoll. In this case the benmoreite may have pre-dated the emplacement of most of the cone.

Neither of these centers are among the younger eruptions. This illustrates the point that although evolved rocks occur, in general, with greater frequency among the younger age eruptions, the most evolved rocks are not necessarily the youngest. It likewise reflects the fact that within typical volcanic fields there are a variety of different magma sources that probably evolve separately, and the degree of evolution need not reflect the timing of such eruptions with respect to the field as a whole or the evolution of a single magma source.

Other examples of viscous lavas were erupted from more typical cinder cones or did not involve the construction of domes. Most such examples are compositionally mugearites, often with unusually large phenocrysts of hornblende or plagioclase. A large flow of mugearitic composition with no apparent vent structure occurs south of Concho near Concho Springs Knoll (vent 2529, estimated 0.90-1.30 Ma).The spatter of Concho Springs Knoll immediately to the north of this flow is compositionally similar to the mugearitic flow, and the vent and flow must be considered to be related, but there is no clear connection between the cone and the flow. One possibility is that the cone grew separately but from the same reservoir, and the main mugearite flow was erupted from a related vent to the south. Other examples of similar relatively thick and apparently viscously erupted flows include those from vents 1634, 9605 (mentioned above for the unusually large size of hornblende phenocrysts in its lavas), and 0634. Burnt Knoll (vent 0512, estimated 0.55-1.10 Ma), 5 km east of Vernon on Highway 60, is a cinder cone with an associated porphyritic mugearite flow (up to 30 m thick) in which plagioclase appears as the dominant phenocryst.

Unusual vents

A particularly unusual vent (9602, estimated 0.30-1.10 Ma) occurs in the central field, 3.2 km west of the Greens Peak-to-Highway 60 forest road and 4 km south of Highway 60. In this case, a pre-existing basalt flow surface was domed up 100 m into a steep cone-shaped rise, or cryptodome, by an apparent near-surface laccolithic intrusion. Magma

FIGURE 17. Cerro Hueco maar seen from the north rim. The view is to the south. Cerro Montoso is the peak in the near distance and Greens Peak area vents at the summit of the field are in the far distance.

subsequently broke through the eastern end of a small east-west graben along the crest of the dome and erupted a thick, short flow of mugearite accompanied by a small amount of vent spatter and agglomerate. The lavas were clearly emplaced after the dome was formed, as indicated by the fact that the lava flow is diverted around the base of the dome. Thus a considerable amount of magma was injected extremely near the surface before eruption of the flow commenced. The relatively minor amounts of pyroclastic material in the vent area suggest that the eruption was relatively volatile-poor compared to many eruptions in the field, perhaps as a consequence of degassing of the magma during formation of dome.

An apparently rootless flow, 3 km long, occurs south of Cerro Hueco (sec.2, T10N, R6E). This is a typical olivine basalt, but it tapers to a narrow ridge at its apparent origin near the base of a long slope from the Cerro Montoso complex of cones and it has no obvious vent materials or uphill source. In the absence of any other obvious mechanism for its emplacement, it is interpreted to represent a relatively quiet outwelling of lava from a small fissure striking N80°E that formed in the side of the regional slope leading up to the Cerro Montoso vent complex. The surface of this flow was also tilted 2-3°NW throughout much of its length during the later tectonic deformation. Similar distortion, warping and back-tilting characterizes many flows in the northern part of the field and illustrates one of the means whereby small amplitude tectonic deformations were detected through detailed mapping.

TRAVERTINE MOUNDS

Travertine mounds occur throughout the valley of the Little Colorado, on the northeast edge of the SVF. Their origin is relevant to understanding the regional structure and the many excellent exposures illustrate an unusually symmetric form of travertine mound development.

Almost all of the travertine occurrences lie in the structural depression bounded on the southwest by the Concho lineament and on the northeast by the Coyote Wash fault trend (Fig. 18).This indicates that the travertine originated when ground water flowed down the hydrologic gradient from the central volcanic field, and was forced to emerge as springs along deep faults on the periphery of the structural depression. Carbonates acquired by the water along deep circulation pathways from the central field outward to the margins precipitated at the surface as the water emerged as springs. Few springs are active (Sirrine, 1958); springs in most of the travertine mounds are currently inactive, reflecting the general drying of the climate and decreased recharge of the deep water table throughout the region in the recent past.

Some travertine deposits in the SVF are relatively featureless, but most are simple cone-shaped features. Although travertine occurs throughout the world in various settings (Chafetz and Folk, 1984; Kendall and Warren, 1987), the unique and elegantly symmetrical structure of the travertine deposits here and at a few other sites in the southwestern U.S. mimics in many respects the morphology and formation of small shield volcanoes (Fig. 19) and appears to have gone largely unstudied. Completing the analogy with small volcanoes, each travertine mound is characterized by a circular summit depression, or spring orifice, which is frequently steep-sided and deep, or shallow and bowl-shaped. Many of the earlier travertine mounds stand as isolated travertine-topped sedimentary buttes due to the downward incision of the Little Colorado and its flood plain, but several travertine mounds,

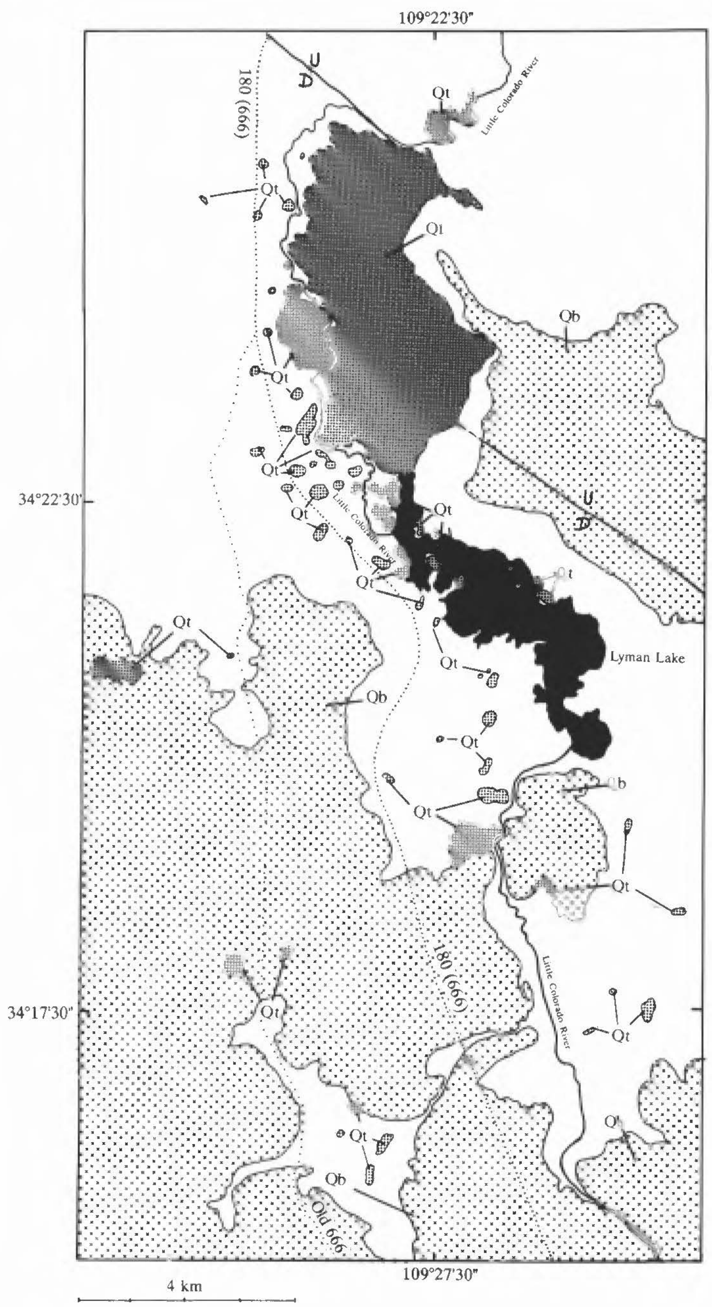

FIGURE 18. Occurrence of spring deposits (Qt) in the SVF. Most of the spring deposits occur in the valley of the Little Colorado River and lie up the hydrologic gradient from a major regional fault (Coyote Wash fault, see Fig. 5). The spring deposits probably formed here when deep carbonate-charged ground water flowing down the hydrologic gradient from the White Mountains and Springerville volcanic field emerged along the Coyote Wash fault zone. Qt - travertine deposits; Qb - basalts of the Springerville volcanic field, undivided; white - sedimentary units undivided.

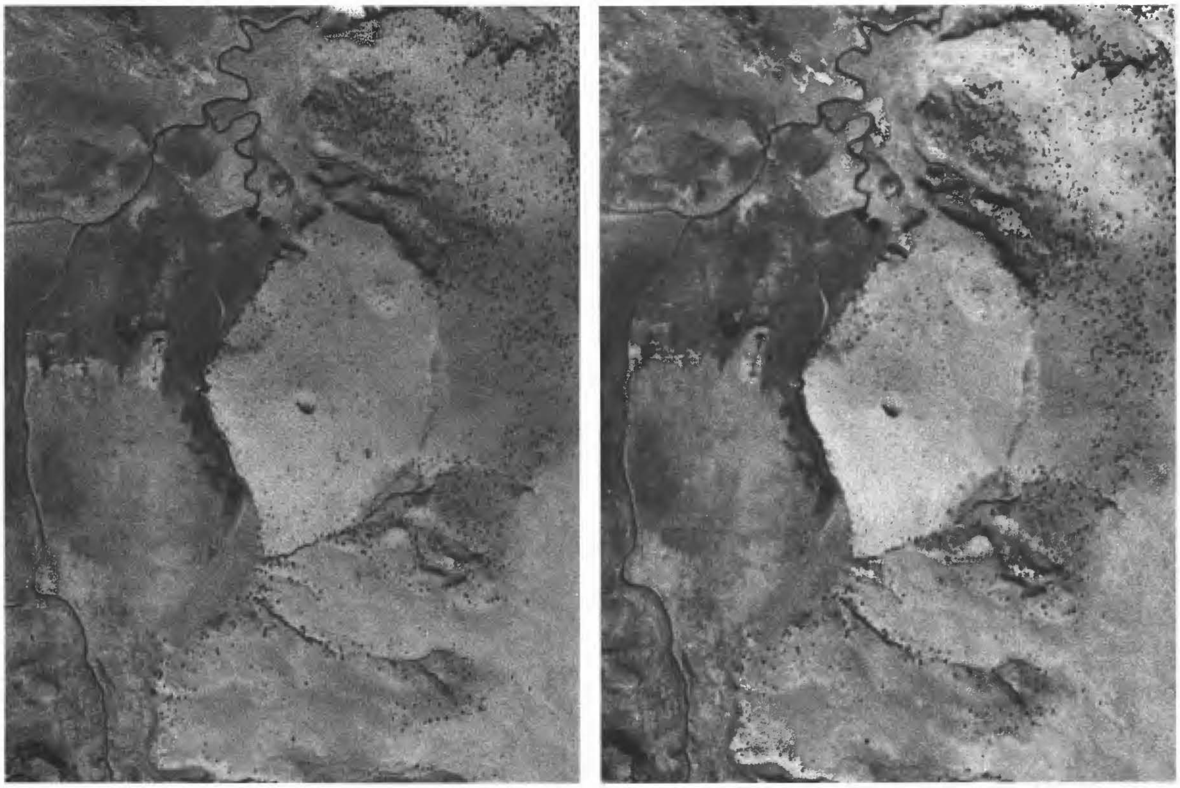

FIGURE 19. A. Stereo air photo pair of a typical small, symmetrical mound-type spring deposit in the northeast margin of the Springerville volcanic field, in the vicinity of the Little Colorado River and Lyman Lake. The travertine mounds are generally characterized by cone-shaped profiles and small summit pits resulting in an appearance similar to small volcanic cones or shield volcanoes. The similarity to volcanic cones is a consequence of the slow accumulation of precipitates from many small spring "discharge events" about a central orifice, analogous to lava flows accumulated about a volcanic vent. Image width is 1 km.

particularly those high on the slopes of the valley are relatively uneroded. One travertine mound is naturally half-sectioned on the east shore of Lyman Lake (Fig. 20). Based on this example, most of these mounds consist of gently dipping alternating dark and light layers, sweeping to a summit where the layering is disturbed by chaotic collapse structures in the immediate vicinity of the spring orifice. Others are simple straight-sloped cones. The origin of the cone or shield-like morphology is probably a consequence of repeated deposition of precipitates from azimuthally random discharges about a stable central spring. Variable rates and distances of discharge owing to seasonal and secular variation in rates of ground water flow probably control the magnitude and lateral extent of each deposition during each cycle and thus control the ultimate slope and form of individual mounds.

CONCLUSIONS

Several broad conclusions about the Springerville volcanic field can be stated on the basis of mapping, analysis of petrologic samples and regional structure, and physical volcanological characteristics. First, the field is petrologically diverse and includes tholeiitic, alkalic and evolved alkalic rock types. These are characterized by a general evolutionary trend in petrology in which tholeiitic rocks account for 24% of the field volume and were erupted early, and alkalic and evolved alkalic rocks (mugearite and benmoreite) were erupted later (Condit et al., 1989a). This might imply that the relative degree of partial melting and the total volume of melts available for eruption diminished steadily with time.

Second, the average volume rate of effusion over the history of the field was 1.5 X 10^{-4} km^3/a (Crumpler et al., 1990). This is similar to rates observed for other cinder cone volcanic fields throughout the world (Fedotov, 1984; Shaw, 1985), and is lower by about an order of magnitude than typical rates associated with large volcanic edifices and calderas characterized by single large magma reservoirs and repeated eruptions from isolated and evolved magmatic centers (Fig. 21). Estimates of the rates of magma supply necessary to maintain large magma reservoirs (Hardee, 1982; Shaw, 1985) imply that volume rates equivalent to those seen in cinder cone fields are slightly less than that necessary for establishing and maintaining a magma body in the crust over periods of several thousand to one million years. Although magma supply in the SVF was long-lived, it has been too low and sporadic to sustain a single large volcano, thus resulting in a concentration of isolated vents.

FIGURE 20. Natural section through a travertine cone (400 m in diameter) exposed on the east shore of Lyman Lake.

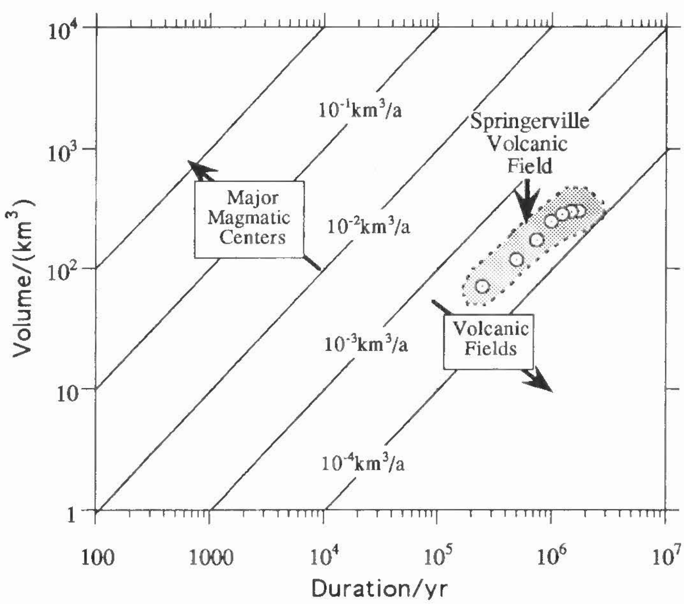

FIGURE 21. Volume-duration plot for the Springerville field, showing the volume rates of eruption for several intervals during the life of the field (open circles). Observed rates of volcanic output throughout the lifetime of the SVF are typical of volcanic fields in general. Based on consideration of the rates of magma replenishment necessary to develop central magma chambers, magma replenishment rates in the SVF, as with many cinder cone type volcanic fields, appear to be lower than that necessary to sustain a central edifice.

Third, the great variety in the style of vents reflects both environmental conditions present at the time of the eruptions and the influence of neotectonic stresses on the orientation and the dynamic characteristics of individual dikes and fissures initiating each eruption. The general absence of strong patterns of fissure vents implies that simple tensile stresses that would favor long fissures have not been present, a consequence perhaps of the interpreted left lateral shear stresses in the brittle crust throughout much of the field. Pyroclastic materials in many of the vents may be more fragmental (less spatter) than elsewhere. This may reflect greater fragmentation resulting from generally wetter near-surface conditions at the time of most of the eruptions, favoring increased participation of non-juvenile volatiles and stronger vesiculation. In addition, the higher magma driving pressures necessary to open and sustain dikes in this tectonic stress environment may have been influential.

Fourth, detailed mapping has enabled us to recognize neotectonic features in this part of the Colorado Plateau, based on folds and faults post-dating uneroded late Cenozoic basaltic lava flows (Crumpler et al., 1989). Quantitative analysis has shown distinct clusters and alignments of vents in the SVF (Connor et al., 1992) and that the boundary of many clusters of vents, as well as the termini of fissure trends and vent alignments, correspond with the location of many large-scale neotectonic faults and folds. Large-scale crustal structure appears to have played a part in localizing vents and concentrating them in clusters. Similarly, fissures appear to be sensitive to variations and discontinuities in patterns of strain in the brittle upper crust. The distance between local clusters of cones (15 to 20 km) may be significant, as this dimension is less than the crustal thickness in the region (Keller et al., 1979), but approaches the thickness of the brittle crust in the Colorado Plateau (Wong and Humphrey, 1989). Although more speculative, the location of vents could be influenced by crustal blocks that are bounded by strong through-going structures. This same regional structure probably influenced the regional ground water flow and contributed to the formation of spring deposits (travertine). Many of the spring deposits are unusually symmetric in shape and reflect steady discharge of carbonate-rich water from central spring orifices.

We interpret the large-scale physiographic and morphologic features in the SVF to be a consequence of limited, very nearly incipient strike-slip faulting along several regional fault zones striking northwest through the field in which strike-slip is accommodated by normal faulting near the ends of the fault zones. The neotectonic characteristics and the volcanism may have originated in part during lithospheric extension across the margins of the Colorado Plateau associated with late Cenozoic clockwise rotation of the Colorado Plateau. Regardless of the origin of the regional deformation responsible for these structures, it is likely that at least some characteristics of distribution and geometry and eruption dynamics of individual vents reflect the influence of contemporaneous tectonic stresses on the ascent and emplacement of magmas.

ACKNOWLEDGMENTS

Mapping of the Springerville volcanic field was supported by the U.S. Geological Survey, Los Alamos National Laboratories, and the Arizona Bureau of Geology. We thank Wolf Elston (University of New Mexico), George Ulrich (U.S.Geological Survey) and Ed Wolfe (U.S.Geological Survey) for their support in making this project a reality. Sue Gaffey (Rensselaer Polytechnic Institute) provided insight into the world of travertines and spring deposits. Steve Cather and Bill McIntosh (New Mexico Bureau Mines and Mineral Rseources) kindly reviewed the manuscript and offered many helpful revisions and insights. We also thank the people of the communities and ranches located in and on the margins of the SVF, especially those residents of Springerville who became our friends during many summers of geologic mapping.

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