in Jenney, J. P., and Reynolds, S. J., 1989, Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 681-700.

NEOGENE VOLCANISM IN ARIZONA: THE RECOGNIZABLE VOLCANOES

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ABSTRACT

Volcanoes that can be easily recognized from their constructional landforms occur in nine basaltic volcanic fields in Arizona and vicinity. These discrete tracts of land, covered with pyroclastic cones and interlocking lava flows, are remarkably similar despite major differences in their geologic settings. Few of the volcanoes erupted more than 100,000 cubic meters of magma, and most were apparently produced in single, continuous, low-explosivity "strombolian" eruptions of short duration. The range of rock composition in any or all of these fields is limited (and predominantly alkali-basaltic) within the population of small volcanoes. This suggests that each volcano came from a single, small batch of magma that was generated by a universal process but that differentiated uniquely. Composite volcanic mountains in the Pinacate and San Francisco fields are much larger and have wider ranges of rock compositions, including trachyte and rhyolite. They were presumably constructed by repeated eruptions from larger, more complex magma batches as those magmas evolved predominantly through fractional crystallization.

Rock compositions and eruption style (as reflected in the landforms) imply that all the fields have a comparable origin from magma sources areally localized in the upper mantle beneath each field. The magmas may have been generated by activity of mantle plumes or of diapirs at depths well below the effects of crustal tectonism. Crustal stress influences magma rise but Uinkaret is the only field where stress has obviously controlled volcano location; chains of contemporaneous cones are parallel to normal-fault traces.

Few of the "cinder cones" are composed of architectural-grade cinder; most contain heterogeneous layers of mixed pyroclasts ranging from millimeter lapilli to meter-sized bombs variously indurated. Some of the layers are simply compacted, others are tightly welded agglutinate or solid, rootless lava flows. Erosion has exploited the varying resistances of layers to create some bizarre landforms. A few of the monogenetic volcanoes are hydro-volcanic maar craters and tuff rings.

Future eruptions are almost certain in the Uinkaret, San Francisco, Zuni-Bandera, and Pinacate fields. Only the city of Flagstaff faces any geologic hazard from this because the low-energy, fire-fountain activity expected will be limited to the immediate vicinity of the vent.

INTRODUCTION

Young volcanoes are striking elements of Arizona's scenic landscape, and the volcanism is an important aspect of regional geology. The distinctive landforms, predominantly small pyroclastic cones, are grouped in discrete volcanic fields located in all three of the state's geologic provinces (figure 1, table I). These volcanoes are the products of the most recent events of an episodic and widely scattered alkali basaltic volcanism that is by no means extinct. Because volcanic landforms are constructional, they are geomorphically fragile—few older than 2-3 million years can still be recognized. Pre-Pleistocene volcanic rocks generally have only erosional landforms—the volcanoes are gone.

The young volcanoes are of two entirely different types, small monogenetic "cinder cones" (a misnomer, as few contain much real cinder) and large composite volcanic mountains. The small volcanoes, clustered by the hundreds in most of the volcanic fields, are called "monogenetic" because each appears to have been created in a single, continuous eruption of probably no more than a few months duration. In contrast, the volcanic mountains—strato-volcanoes that occur along with the small cones only in the Pinacate and San Francisco fields—are piles of interbedded lavas and pyroclasts extruded in numerous

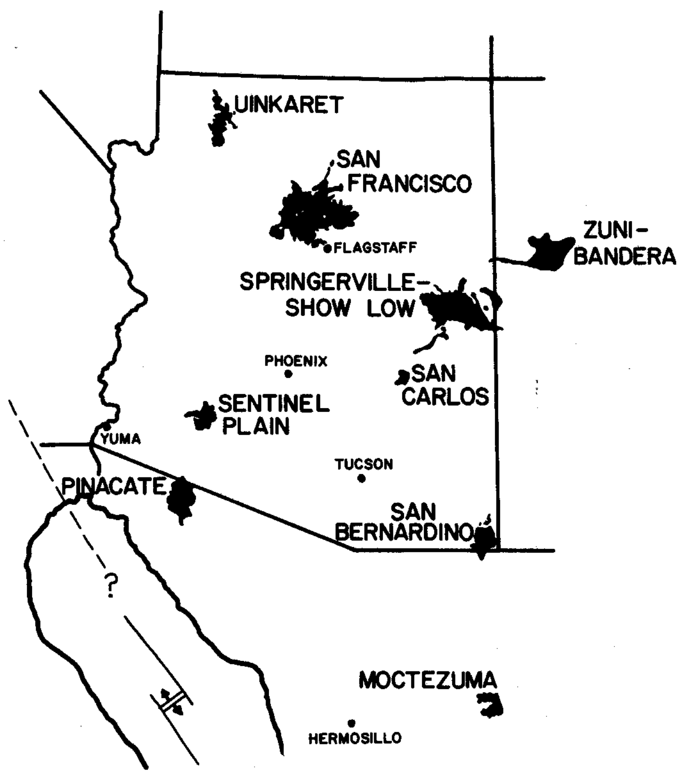

Figure 1. Fields of Plio-Pleistocene age volcanoes in the Arizona region. Uinkaret, San Francisco, Zuni-Bandera and Pinacate are potentially active. Occurrences of Pliocene basaltic rock that are older than 3 Ma, lack easily recognizable constructional landforms and are omitted. The general characteristics of each field are summarized in table 1.

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Table 1. SUMMARY OF CHARACTERISTCS OF ARIZONA'S PLIO-PLEISTOCENE VOLCANIC FIELDS

Name And Location	Area sq km	Altitude m	Tallest Cones	Volcano types and numbers	Rock Types
Uinkaret 36°-30′N 113°-10′W	830	1300	200m	Scoria cones—250	Alkali basalt Hawaiite/Bas. andesite Ankaramite Quartz basalt
San Francisco 35°-20′N 111°-50′W	5000+	2000	330m	Scoria cones—500+ Maar/tuff ring—5 Composite—4	Alkalic Basalt Benmoreite-trachyte Calc-Alkalic Andesite—latite Dacite—rhyolite
Springerville-Show Low 34°-20′N 109°-40′W	3000+	2000	300m	Scoria cones—400+ Maar—1	Basalt Hawaiite—mugearite Benmoreite
San Carlos 33°-15′N 110°-25′W	50	1000	eroded	Cones—5 Maar/tuff ring—1	Basalt
San Bernardino (Geronimo) 31°-30′N 109°-15′W	850	1300	150m	Scoria cones—135 Maar craters—5	Basalt Hawaiite
Moctezuma 29°-35′N 109°-35′W	300	700	20m	Lava cones—5	Basalt
Sentinel Plain 32°-50′N 113°-10′W	750+	160	75m	Lava cones—20	Basalt
Pinacate 31°-50′N 113°-30′W	1500	200	150m	Scoria Cones—425 Maar/tuff ring—13 Composite—1	Basalt—hawaiite Hawaiite—trachyte
Zuni—Bandera 34°-50′N 108°-20′W	2500+	1500	100m	Scoria cones—74	Alkali basalt Tholeiitic basalt

NOTE: Latitude and longitude of the approximate center of each field.

eruptions over hundreds of thousands of years. Except for the more or less conical shape that has resulted from addition of material at summits, each type has different landforms and structures. The differences reflect the various eruptive behaviors of heterogeneous magma compositions, a wide variation of erupted volumes, and contrasting opportunities for erosion.

Presence of these fields in Arizona suggests three important questions. Why are Arizona's young volcanoes predominantly cinder cones composed of alkali basalt? Why are they clustered in small fields and not broadly distributed? Are the processes responsible for generation of the magmas reflected in any other aspect of the state's geology?

Eldred Wilson in his 1962 Résumé of Arizona Geology was able to devote only two pages to *all* of Cenozoic volcanism because, at that time in the development of Arizona geology, neither the necessary analytical equipment nor the professional interest was available to unravel the petrologic complexities. Much has been learned in the quarter century since that time. This paper is an overview of the young, recognizable volcanoes and their rocks in Arizona and adjacent borderlands. Landforms and structures are similar in all the subject volcanic fields regardless of location. The predominant rock type erupted since mid-Pliocene time has been alkali-olivine basalt, and the greatest amount of geochemical data is available for rocks of Arizona volcanic fields that still have their volcanic landforms.

Rocks and Magmas

A volcanic eruption is the end result of processes that begin in rocks far beneath. The landform is only the top part of a magma system that comprises a source, some kind of storage chamber, and a conduit to the surface. Magma is generated by thermal and dynamic processes acting within the source to break bonds in minerals and release ions. The free ions accumulate as liquids that migrate through the

Nodules	$^{87}Sr/^{86}Sr$	Ages Ma	References
Lherzolite Garnet Lherzolite Pyroxenite Gabbro	0.7029– 0.7041	7.0—Holocene	Best, 1970 Best and Brimhall, 1974 Best and others, 1980 Leeman, 1974
Pyroxenite Gabbro	0.7026 0.7050	6.0—Holocene	Damon and others, 1974 Leeman, 1970 Moore and others, 1976 Smiley, 1958 Tanaka and others, 1986 Wolfe, 1984 Wolfe and others, 1983
Gabbro	0.7036 0.7053	2.1—0.3	Condit, 1984 Crumpler and others, 1986 Laughlin and others, 1976 Laughlin and others, 1971 Leeman, 1970
Lherzolite Pyroxenite	0.7035	4.2—1.0	Frey and Prinz, 1978 Leeman, 1970 Shafiqullah and others, 1980 Wilshire and Shervais, 1975
Lherzolite Pyroxenite Gabbro	0.7029– 0.7034	3.2—0.3	Evans and Nash, 1979 Kempton and others, 1982 Lynch, 1978 Menzies, 1983 Menzies and others, 1985
None reported	0.7034	None dated	Lynch, unpublished Paz-Moreno, 1984
None reported	0.7035	3.2—2.0	Leeman, 1970 Lynch, unpublished Shafiqullah and others, 1980
Lherzolite (rare) Pyroxenite Gabbro	0.7030– 0.7042	1.7—0.12 +Holocene	Donnelly, 1974 Gutmann, 1972 Lynch, 1981
Lherzolite	0.7027– 0.7034	3.8—0.2 +Holocene	Ander and others, 1981 Leeman, 1970

rock and collect into coherent magma bodies. These bodies of liquid, probably in some kind of connected spaces (magma chambers) separated from their source rocks, evolve independently to produce the wide variety of volcanic rock types found on the surface.

Magma generation is a characteristic process on both convergent and divergent plate boundaries. But Arizona's alkalic lavas are neither the product of subduction nor of seafloor spreading; they differ both in composition and distribution from either subduction-zone or spreading-center-related rock associations. Volcanism associated with the subduction zone responsible for the mid-Tertiary orogeny, between about 30 and 15 Ma, yielded a complex array of intermediate and silicic volcanic rocks across southern Arizona (Coney and Reynolds, 1977; Damon and others, 1981; Shafiqullah and others, 1980). This relatively intense "orogenic" volcanism that accompanied crustal deformation was supplanted by the widely dispersed basaltic volcanism as the crust cooled and thickened (Damon, 1971).

Divergent-margin volcanism is active in the nearby Sea of Cortez (Gulf of California). Mid-ocean-ridge-type tholeiitic basalt (MORB) has been produced on spreading centers that join segments of transform fault for the past 4-6 million years (Elders and Beihler, 1975; Terrell and others, 1979).

The predominance of alkali-olivine basalt (AOB) and derivative alkalic rocks provides the main key to understanding the origins of Arizona's young volcanoes. Schwarzer and Rogers (1974) investigated distribution of alkali-basalt occurrences worldwide and found that this type of volcanism occurred in all plate tectonic settings, not only intra-plate but on both divergent and convergent boundaries. They interpreted this distribution to signify that the magma was generated too far down in the mantle to be affected by any major crustal tectonism including plate-boundary processes. Norry and Fitton (1983) pointed out the lack of significant difference between alkali basalts of oceanic areas and continents, concluding that the sources of the magmas " . . . must therefore lie beneath the lithosphere, since any significant involvement of lithosphere (including the crust) . . . would have produced differences (in composition)."

Alkali-olivine basalt magma is undersaturated in silica and enriched in large-ionic-radius lithophile (also called incompatible) elements. It is the product of small-fraction partial melting of mantle peridotite (Gast, 1968; Ringwood, 1975; Yoder, 1976). The nature of the peridotite source has been inferred from presence of dense nodules of olivine and pyroxene (with spinel, garnet, kaersutite hornblende, and phlogophite mica as possible accessory minerals), which are relatively common in lavas and tephras of AOB volcanoes all over the world. Several Arizona fields are important sources for these "ultramafic" nodules (table 1); the San Carlos field is a classical locality. The nodules have been recognized as fragments of the mantle from the earliest days of petrology and have been the focus of what Harte (1983) characterized as a " . . . relentless search for the *average* composition of the mantle," a search now known to be unrealistic. The nodules are neither pieces of an undifferentiated mantle nor are they the residue from generation of the magmas that brought them to the surface; their histories are much more complex (Menzies, 1983).

The exact relationship between nodules and basalts remains a subject of controversy. Experimental work has determined that basalt magmas of remarkably uniform major-element composition can be generated from partial melting of many of the mantle rock types found as nodules and that the same starting material can yield either alkali-basalt or tholeiite, depending on whether a small or large fraction of the source is melted (Ringwood, 1975; Yoder, 1976). However, if we assume that the average mantle has trace-element abundances equivalent to those of chondritic meteorites, the typical AOB concentrations of incompatible trace elements require very small degrees of partial melting, far less than 1 percent in some extreme cases (Gast, 1968).

Gast's (1968) suggestion was initially controversial because of a perception that very small fractions of melt could not be extracted from a solid matrix. Liquid in tubular or planar interstices between effectively inelastic crystals cannot be easily removed because of the energetics of wetting. Experiments with nodules found that melt volumes smaller than 5 percent were immobile (Arndt, 1977). These objections have been countered by Fowler's (1985) mathematical modeling of asthenosphere melting wherein pore pressure can exceed lithostatic pressure by several hundred MPa (100 MPa (mega-Paschals) equals 1 kilobar), so that vanishingly small melt fractions might well be quite mobile.

Whereas trace-element concentrations in the rocks suggest that the mantle source was enriched, isotopic ratios of Sr and Nd show that the sources of the modern magmas were depleted in incompatible elements by a melting episode long in the past. This "decoupling" of isotopic ratios from large-ion trace-element concentrations requires some mechanism by which the necessary elements could have been added to the sources of the modern basalts recently enough not to have disturbed the "ancient" isotopic signature (Kempton and others, 1982).

Some geochemists have asserted that "plumes" bring the incompatible elements (from an external source) into the zone of melting (Anderson, 1981; Menzies and Murthy, 1980; Wass and Rogers, 1980). This idea is appealing because the mechanism also allows for influx of heat and volatile elements from the plume to promote melting (Lynch, 1981). Other geochemists (Feigenson and others, 1984; O'Hara, 1985) suggested that all the required trace elements are available in the source volume, that they can be concentrated by the melting process, and need not be imported. O'Hara (1985) suggested that AOB magmas are generated by decompression melting of rising mantle diapirs, which requires neither influx of heat nor of fluids to the source rock. Incompatible elements are extracted from the source as the magma flows through thin dikes.

Compositions of the rocks we collect cannot indicate whether the magma is produced by "batch melting," in which the liquid remains in chemical equilibrium with the source matrix until extracted as a batch, or the liquid is extracted as it is produced by "disequilibrium partial melting." The magma may be evenly distributed over the source volume (McKenzie, 1984) or concentrated in closely spaced schlieren dikes (Maaloe and Johnson, 1986) until the volume is tapped and the magma conveyed to the site of a magma chamber.

Magma Evolution and Derivative Rock Types

Basanite, basalt, and hawaiite are the most common rock types in the small volcanoes; very few have andesite, mugearite or benmoreite (Condit, 1984; Lynch, 1981; Nealey, 1987, personal communication). Relatively little compositional variation is found within these small volcanoes. The greatest variation and the most evolved rock types, the trachytes and rhyolites, are restricted to the composite volcanic mountains or to large dome complexes. Inferences about magma generation and accumulation can be drawn from these observations.

Primary magmas, those liquids generated from and in chemical equilibrium with minerals of the mantle source, apparently never reached the surface in the Arizona region. Rock representing a primary magma can be identified from its concentration of magnesium relative to ferrous iron expressed as "magnesium number" or Mg* (100 × MgO / MgO + FeO)(Frey and others, 1978). A magma in chemical equilibrium with mantle olivine should have Mg* between 68 and 75, and no Arizona analyses meet this minimum criterion (Nealey and Sheridan, this volume).

Variations of rock composition among the small volcanoes of each field and within the few large volcanoes suggest that magmas must be stored for some period of time as connected, mixing bodies in some kind of magma chamber. Although magma compositions change somewhat through wall-rock metasomatism as the liquid wends its way from the source to the surface, the most significant variations of rock composition are best explained by fractional crystallization. This requires a space where volumes of liquid can mix as constituents are removed, because it is unlikely that the body of liquid involved in an eruption (or in several) could evolve so uniformly if it were disseminated in pores rather than connected.

Migrating primary magma collects in a magma chamber at some depth where it differentiates. As a magma body cools and crystallizes, liquid volume decreases with the removal of constituents. Mobility is affected as increasing silica concentration raises viscosity and neutrally buoyant entrained phenocrysts form; a magma that contains more than 50 percent phenocrysts (by volume) cannot flow (Marsh, 1981).

An eruption requires the availability of at least enough mobile magma to fill a conduit from the storage to the surface. Flow of magma from a chamber to the surface appears to be a threshold-controlled phenomenon. Density contrast between magma and surrounding rock is the most plausible driving mechanism for magma rise (Wilson and Head, 1981). Upward movement begins as the pressure within the chamber exceeds the minimum stress in the rock above it, and flow continues until the weight of the magma in the conduit balances the pressure in the magma chamber, halting the eruption of that particular batch.

The field appearance of most small volcanoes suggests that each cone was constructed in a single continuous eruption of short duration. Erupted volumes are generally less than 10 million cubic meters, and heat losses that freeze the conduit limit eruption durations to a few months, at most (Wilson and Head, 1981). Small volcanoes are monogenetic (one eruption) because insufficient magma remains in a chamber after the end of the eruption to support another one through the same conduit.

In contrast, large volcanoes, with their multiple eruptions and diversity of rock types, appear to have come from large magma bodies that persisted over long periods of time. Consider the rocks of Volcan Santa Clara, a classic suite of alkalic lavas (Lynch, 1981). The alkalic rock clan is characterized by mutual increases in silica, alkali elements, and incompatible trace elements (Cox and others, 1979). All the Santa Clara rocks were apparently derived from a single magma body and were erupted at different times through the same conduit system as the composition of the magma body changed. Compositional variations can be explained (modeled mathematically) by early crystallization and removal of olivine, aluminous clinopyroxene, and spinel and by later crystallization of plagioclase, alkali-bearing pyroxene, and ulvospinel as the magma cooled. Other evolutionary processes such as injection of fresh magma may have been involved but fractional crystallization explains most of the observed variation. Volume computations suggest that an initial magma body volume of at least 100 km^3 was necessary to account for the evolution of the analyzed rocks (Lynch, 1981).

The volcanic mountains in the San Francisco field have a much greater variety of rock types and a wider distribution of volcanoes than in Pinacate. This suggests a much more complex mechanism for magma genesis and evolution. The large San Francisco Mountain and four adjacent smaller eruptive centers—Bill Williams Mountain, Sitgreaves Mountain, Kendrick Mountain, and O'Leary Peak—are unlike any of the other eruptive centers in that region (Wolfe, 1984). They have a great diversity of lavas, from alkalic rocks, like those of Santa Clara, to calc-alkalic andesite, dacite, and rhyolite (Gust and others, 1984; Wenrich-Verbeek, 1979; Wolfe and others, 1983). This diversity cannot be explained by fractional crystallization, either simple or multi-stage, (Gust, personal communication, 1984). Some of the rocks in the main massif possibly constitute separate differentiation sequences from more than one magma body (Wenrich-Verbeek, 1979). Some rocks of the San Francisco Mountain may be "hybrid," generated in part by assimilation of lower crustal granulites by basaltic magma (Gust and others, 1984).

Not all "monogenetic-appearing" volcanoes have simple histories. The building of Sunset Crater and effusion of the Bonito lava may have been separated by at least several tens of years based on paleomagnetic measurements (Champion, 1980). Dohrenwend and others (1984) reported K-Ar ages differing by as much as 200,000 years on separate lava flows appearing to have issued from single conduits in the Cima Volcanic field of California.

The great preponderance of small, monogenetic volcanoes in Arizona's late Neogene alkalic volcanic fields suggests that magmas do not ordinarily accumulate in large volumes before they begin to differentiate and approach the eruption threshold. Cones of a wide age range, containing variously differentiated rock types, are scattered randomly across the areas of most fields because magma generation beneath a field is a more or less constant process. Time-space scattering of the volcanoes is a consequence of magma accumulation and evolution.

Collection of large magma batches is unusual, but in those few bodies, magma chamber overpressure occurs at intervals. Single eruptions do not exhaust the chambers, and liquid remains to differentiate so that each succeeding eruption brings up slightly more evolved magma to form a genetically related sequence of rocks. Rejuvenation of a magma body by injection of new magma can yield two or more sequences on the same edifice (Cox and others, 1979). This may have happened in the San Francisco Mountain volcano (Wenrich-Verbeek, 1979).

Tectonics and the Alkaline Volcanism

The association of volcanoes with both divergent and convergent plate margins, major tectonic features of the crust, makes inescapable the possibility that all volcanoes are associated with some kind of tectonic feature. Two pillars of conventional wisdom in geology link volcano location to crustal structure. First is the association of a volcano or a field with a mapped fault or fault zone, and second is the appeal of alignment—the volcano or volcanic field of interest is part of a perceived chain, a "lineament."

A few volcanoes do lie directly on fault traces. Cinder cone groups in the Uinkaret field are atop, or aligned parallel to, major normal faults on the western margin of the Colorado Plateau. Investigators in the San Francisco volcanic field postulate a strong link between sites of the silicic volcanoes and both the Mesa Butte and Oak Creek—Doney fault systems (Shoemaker and others, 1978; Tanaka and others, 1986). Magma exploiting the break as a conduit is seen as the causative link between fault and volcano. An old idea, now discredited, considered that slip on some faults promoted decompression melting in the mantle source, and the magma then followed the fault to cause the eruption. Geophysical evidence, particularly seismic profiling of the crust (Allmendinger and others, 1987; Potter and others, 1987), indicates that normal faults, at least in the Basin-Range province, do not penetrate through the entire crust and thus can neither act as magma conduits from the mantle nor influence the mantle in any way. The lower part of the crust may not be sufficiently brittle to "fault," and there is good evidence that faults that are steep at the surface may curve to shallower dips at mid-crustal depths. But fault zones such as the Mesa Butte, a complex structure of great antiquity (Shoemaker and others, 1978), cannot be dismissed as possible guides for magma diapirs in the crust.

The observation that a group of volcanic fields forms a line or narrow band suggests the influence of some hidden factor. The "Jemez lineament" encompasses the Pinacate, San Carlos, Springerville, and Zuni-Bandera fields (Laughlin and others, 1976). Smith and Luedke (1984) searched for some "systematic distribution pattern" for the late Neogene volcanic fields of the western United States. They were able to define a rectilinear grid, including the Jemez lineament, that contained all the fields, but their zones are broad and do not have the tight "authority" of volcanic arcs that are aligned by their genetic relationships to subduction zones. The source of AOB magma "well below the lithosphere" suggests that if Smith and Luedke's zones are significant of anything, they reflect conditions within the mantle rather than anything directly related to crustal structure.

One other alignment is worthy of mention in this context: the Uinkaret, San Francisco, and Springerville-Show Low fields lie near the edge of the Colorado Plateau. The possibility that their positions are somehow related to tectonic processes along this major province boundary has intrigued almost every investigator of Arizona geology but no satisfactory explanation has ever been proposed to explain their positions.

"Lineaments" are part of a controversy about magma availability; either magma is generally available beneath the crust and the volcanoes mark places where crustal weaknesses allow it passage, or volcanic fields are constructed directly above unique zones beneath the crust where magmas are being generated and the crust cannot hold the magma down. I favor the latter idea because no major difference can be found in rock type, volcano distribution, or field size between the Arizona fields on the thick crust of the Plateau or the thin crust of the Basin-Range, and because volcanoes are not broadly distributed but are limited to discrete fields within the pervasively faulted Basin-Range province.

Another observation links volcanic fields to specific sites of magma generation. Vink and others (1985) showed that volcano ages can be used to trace the movement of plates over approximately fixed mantle hot spots. At least permissive evidence of this can be found in two Arizona fields. Best and others (1980) found a northeastward "shift" of volcanism in the Uinkaret field, but their data set was small and the base line short. Tanaka and others (1986) have analyzed a large amount of data from the San Francisco field and have established a similar time-dependent shift toward the east and northeast.

Although generation of magma is independent of crustal (lithosphere) tectonics, the crustal stress field does control the shape of the conduit and, in a limited way, cone location on the surface. As magma intrudes through rock that is subject to a triaxial differential stress field, it forms a dike perpendicular to the minimum principal stress (Fedotov, 1976; Roberts, 1970). Hydraulic fracturing forms a dike having a length-to-width ratio of 10^3 to 10^4 at lower crustal depths that shortens and thickens at higher levels as Young's modulus decreases (Fedotov, 1976). A dike of long, thin cross section tends to become circular at progressively higher levels. This conduit may intersect the surface as a dike to form a fissure source, it may bifurcate into several branches at a shallow depth to feed a line of simultaneously active cones, it may be nearly circular but sufficiently asymmetric to create an elongate cone, or it may become circular and form a round cone. Fissures, chains of cones, and elongate cones can be used as indicators of a "minimum horizontal compression" (MHC) direction in the crust (Nakamura, 1977).

The Uinkaret field is a classic area to illustrate the relationship between cone distribution and crustal stress field (fig. 2). Not only are the cones aligned in parallel chains, but the chains are more or less parallel to a series of normal faults, some of large displacement, that cut the western edge of the Colorado Plateau (Hamblin, 1970). With an assumed vertical maximum principal stress in this area of extensional faulting, the MHC direction is east-west, at right angles to the cone chains and most of the normal faults. Not all fault traces are perpendicular to MHC but are at angles of up to 30° to this direction, as explained by Reches (1978, 1983). Zuni-Bandera (Ander and others, 1981) lacks chains of contemporaneous cones but contains many cones that are elongate in a northeasterly direction, parallel both to the long axis of the field and to a subsurface structure identified by geophysical methods. Even though surface fault traces are not structural elements, in Zuni-Bandera, the cone orientations suggest a northwest-southeast-directed MHC.

The action of crustal stress is manifest *only* if cones seen to lie in a chain were fed from the same dike-conduit. Lines of cones that are not coeval may reflect factors that control magma storage and rise, but such lines are more likely happenstance and are noted only because of the human desire to find order. Any assertion of tectonic significance to cone distribution must be supported by more than simple alignment.

The Nature of the Landforms

Volcanic landforms fall into three broad categories: composite volcanic mountains, monogenetic cones of various types, and lava flow surfaces. As constructional landforms, they are created out of equilibrium with the local drainage and are easily eroded. All the state's volcanic fields, except San Carlos, have numerous ordinary "cinder cones" on land surfaces covered with overlapping and interlocking lava sheets. Maar craters and tuff cones, hydro-volcanic features that resulted from the interaction of basalt magma with ground water, occur in about half of the volcanic fields. Large volcanic mountains can be found only in the San Francisco and Pinacate fields. In addition to the size distinction between the monogenetic cones and the composite volcanoes, the nature of the small volcanoes differs within and between fields.

The Composite Volcanoes

Pinacate has a single composite volcanic mountain; the San Francisco field has several. These mountains are strato-volcanoes built of layers varying in consistency from solid lava to loose pyroclastic deposits. Geometrical relationships between different units in strato-volcanoes can be complex because erosion in the periods between eruptions removes and redistributes material, carving pathways that influence the flow of lavas from later eruptions. Further complication comes from viscous, gas-poor magmas intruded as plugs or erupted as domes on the mountains.

Volcán Santa Clara, the trachyte-shield volcano of Pinacate (fig. 3), is a broad, shield-shaped volcano composed mainly of thin lava flows that dip gently outward and have little pyroclastic material between them. Most of these lavas appear to have been of low viscosity when erupted. Trachyte plugs or domes were intruded near the summit.

San Francisco Mountain is larger, steeper, and much more complex than Santa Clara (fig. 4). The main massif is a "truncated strato-volcano composed of porphyritic andesite and dacite flows with interbedded pyroclastics" (Wolfe and others, 1983). In addition to growth by accumulation of material on the surface, this volcano grew internally by intrusion of dikes and plugs now exposed in the walls of the Inner Basin. This Inner Basin, modified by glaciers at various times in the past, may be partially the result of explosion or of summit collapse (Wolfe and others, 1983).

In both the Pinacate and San Francisco fields, the composite volcanoes are surrounded by numerous monogenetic cones, but the relationship of the cones to the mountains differs between the fields. In neither place are the small volcanoes "parasites" or "satellites" of the larger mountains; that is, they were not fed from the same magma chambers. Whereas the slopes of the composite volcanoes in the San Francisco Field have few monogenetic cones, the

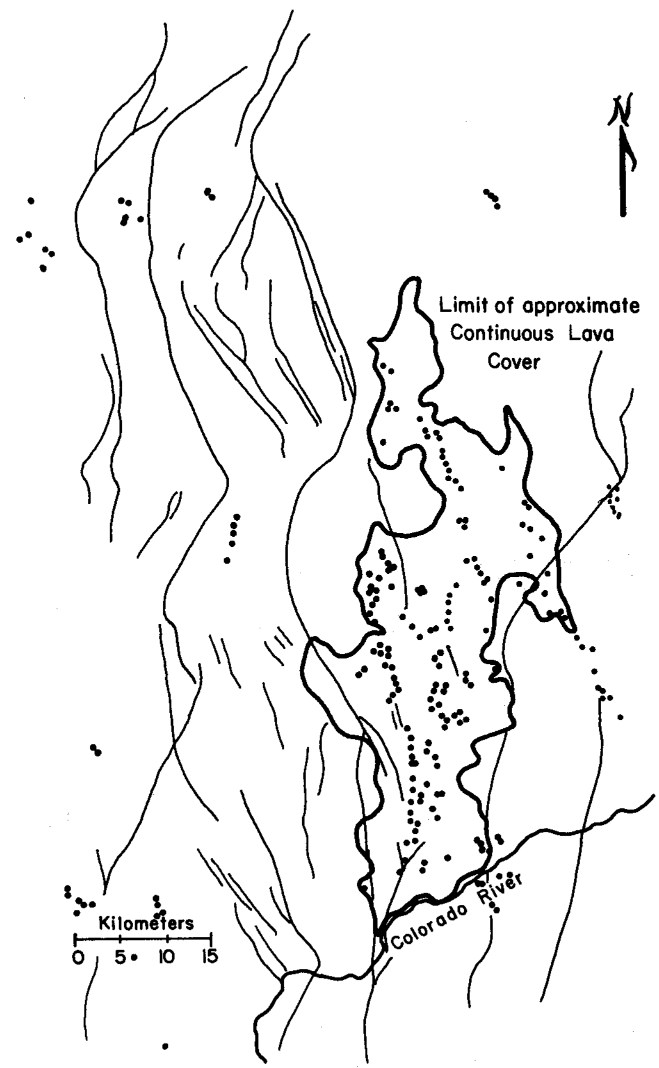

Figure 2. Sketch map of the Uinkaret volcanic field (after Hamblin, 1970). Cones in this field are clearly aligned in chains essentially parallel to the traces of major normal faults. An east-west directed minimum horizontal compression in the crustal stress field explains both the orientations of the cone chains and of the faults. No other field in this study shows the same degree of crustal stress control of magma rise.

Figure 3. Volcán Santa Clara and the Pinacate cones. This trachyte shield volcano is almost completely buried beneath lavas and tephras of the younger Pinacate volcanoes that provide the steeper element of relief on the flanks of the shield. In the foreground is the sand-filled hummocky pahoehoe surface of the Ives flow. P. Kresan photo.

rocks of Santa Clara in Pinacate are almost completely hidden beneath lava and tephra of many smaller, younger volcanoes. These small volcanoes have brought up nodules of cumulate-textured gabbro that are interpreted to be fragments of the material crystallized out of the Santa Clara magma as it fractionated (Lynch, 1981). For San Francisco Mountain where the lavas are more silicic, Wolfe and others (1983) suggested that the lack of monogenetic volcanoes on the mountain slopes might possibly have been the result of a magma chamber "shadow effect," in which dense basalt magma could not penetrate the lighter, evolved magma.

The monogenetic volcanoes

Except for presence of composite volcanoes, both Pinacate and San Francisco are similar to the other monogenetic volcanic fields in the region. Ranges of K-Ar ages and of erosional morphologies in all these fields show that the activity was sporadic over the past few million years. Only rare monogenetic volcanoes erupted more than 10 to 100 million cubic meters of lava.

The typical "cinder cone" monogenetic volcano has two distinct components, the pyroclastic cone and the accompanying lava flow or flows (fig. 5). Whereas flow

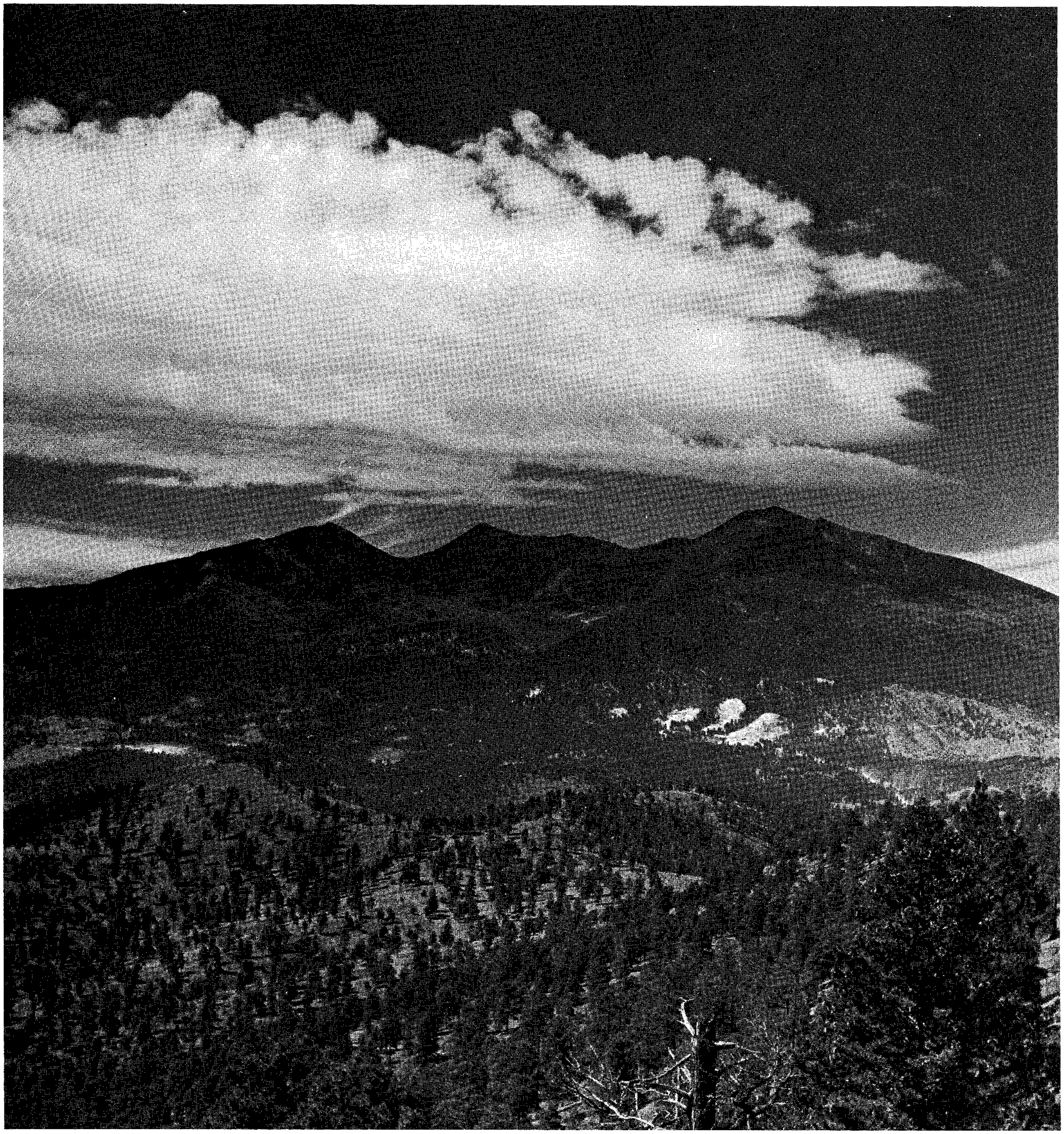

Figure 4. San Francisco Mountain. This photograph, taken from the northeast, looks into the Inner Basin. Note the difference in the shape of this mountain as compared to Santa Clara (both photos taken about 15 km from summits). D. Lynch photo.

lavas and pyroclasts are mixed and stacked in the composite mountains, they are usually separate entities in the small volcanoes. Most cones have a heterogeneous internal composition; the layers are welded to varying degrees, and size sorting within layers is generally poor. Most cones have circular bases and the majority are breached; part of the wall has been disturbed or removed by outward flow of lava. Modern cones of this type are constructed by low-explosivity, fire-fountain eruptions of the type called "strombolian."

The flow lavas effused continuously without disruption and, being relatively solid, contain the greatest part of the

Figure 5. Tesontle, a typical cinder cone volcano. The northwest wall was breached by outflow of lava which carried large masses of bedded pyroclastic material away from the vent (foreground and right). Prior to breaching, Tesontle had a nearly circular base like the small cone in the background. The cinder mine operation visible on the left side of the cone in this 1973 photograph grew to engulf most of the east wall. D. Lynch photo.

erupted mass. The erosional resistance of basalt has preserved some features of the land surface, and radiometric ages have been used to study landscape evolution (see Damon and others, 1974, on the evolution of the Little Colorado River).

Pyroclastic cones are generally smooth when new but may take on a variety of sharp shapes as they erode (fig. 6). Lava surfaces are of sharp relief when fresh, but spines are fragile, and the rough surface tends to accumulate detritus in a short time, so that flow tops can lose their character

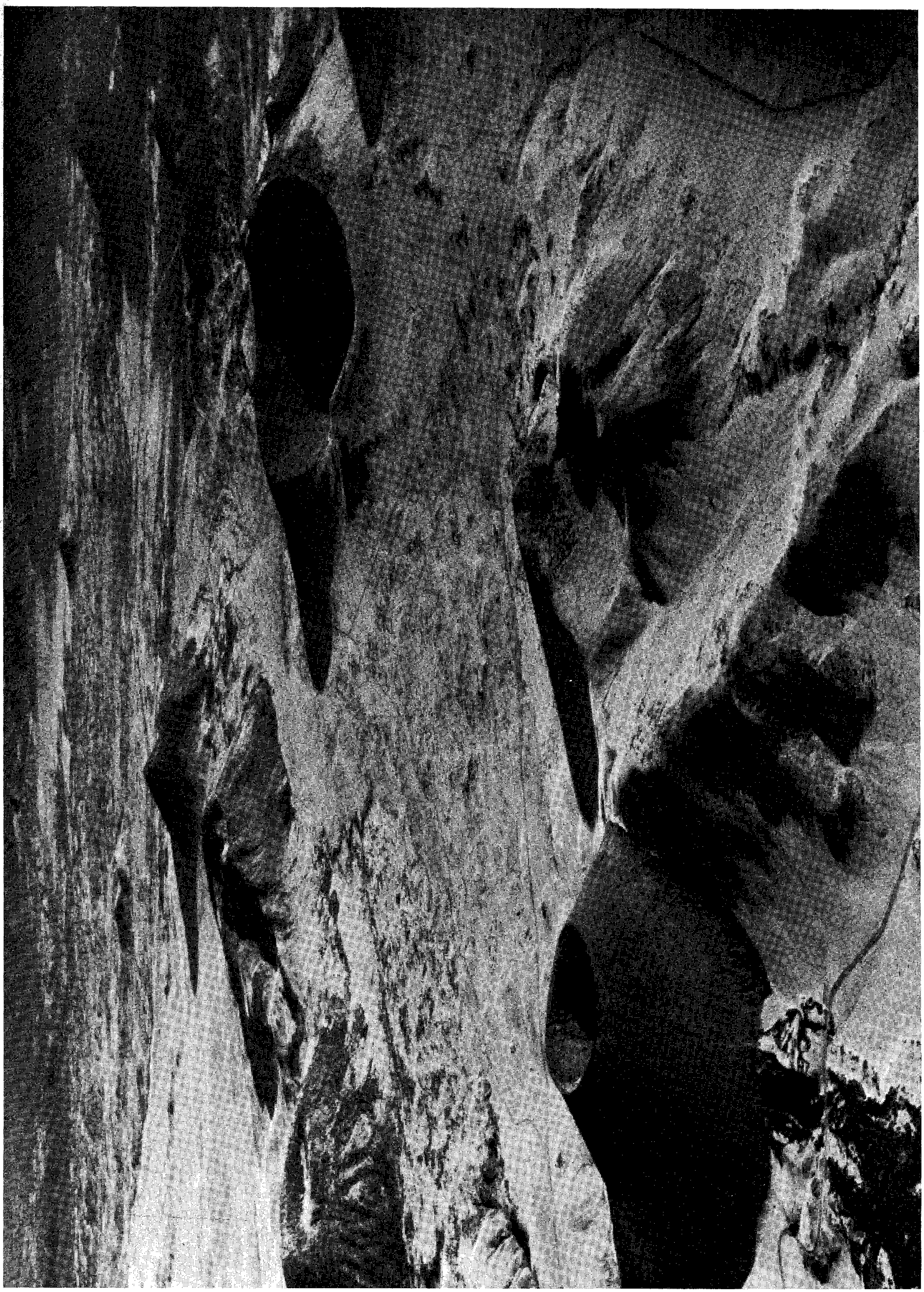

Figure 6. Cones of various ages in the San Francisco field. The age dependence of cone morphology obvious from this photograph is characteristic of all the fields. SP (lower left), one of the youngest cones in the field, has a few shrubs but little grass on its slopes. The others are grass covered and gullied. Colton crater (Crater 160—upper right) is a hydro-volcanic tuff cone. P. Kresan photo.

before cone slopes show much modification. Over time, cone shape becomes diverse and internal structures are exposed. Over the same time, lava flows become buried and surfaces take on a kind of uniformity.

Pyroclasts exhibit a range of sizes, densities, and degrees of welding that reflect conditions of expulsion, flight, and impact. Basalt eruptions rarely produce fine dust or sand because the inherent low viscosity of the magma allows easy egress of the volatiles. Centimeter-sized cinder is the most common small basalt pyroclast; sizes range upward to bombs larger than a meter. A few bombs are dense, most are scoriaceous to varying degrees, and some are as light as cinder. The most scoriaceous of pyroclasts rarely weld on landing (although cinder may be compacted into coherent masses), but the denser fragments may be partially to completely molten on impact and may either form layers of agglutinate (welded scoria) or coalesce into sheets of liquid (rootless lavas) that flow downslope. The degree of welding in the various layers of a cone determines what shape it takes as it erodes.

Strombolian eruptions are complex events with variable energy release; even the most detailed study of an eruption's products may not reveal the scenario. Blackburn and others (1976) studied strombolian dynamics at Stromboli in Italy and at Heimaey in Iceland and noted the complexity of the interaction between volcanic explosions and tephra entrainment in the convective cloud driven upward by the heat of the eruption. Eruptions at Heimaey progressed by a series of explosions that occurred simultaneously with effusion of lava: "Each explosion commenced with rapid, near-vertical rise of a cloud, consisting of a mixture of incandescent pyroclasts and gas." (Blackburn and others, 1976). Sorting began in this cloud as the various fragments decelerated independently according to their sizes and densities. The larger bombs assumed ballistic trajectories, while the smaller, lighter material was entrained in the convective cloud to fall out at various distances downwind. The pulsating explosions were attributed to the bursting of large bubbles (some of 10-m diameter were observed at Heimaey) in the vent mouth, and the large pyroclasts were made by tearing apart the magma constituting the bubble skin.

A few cones are true "cinder" cones, constructed entirely of well-sorted, uniform-size cinder. Cinder is produced under conditions in which bubble nucleation and growth is so rapid that the bubbles interfere with one another as they grow, stretching the liquid basalt into thin skins between them (Sparks, 1978). The basalt is kinematically no longer a liquid but is a transitional material that exhibits brittle behavior in the stress environment of an eruption, fracturing into angular fragments. Cinder is completely disrupted magma; no bands of liquid remain unfrothed. Because cinder is of such low density, the particles are easily entrained in the convective cloud and can be carried considerable distances away from the cone. Widespread cinder blankets occur in many of the fields; the Sunset Crater cinder blanket covers several hundred square kilometers.

Cinder is the most important economic product of Arizona's volcanic fields; cones are currently being mined in the Pinacate, Springerville, and San Francisco fields. Because of its uniform size and jet-black or bright-red colors, cinder is an important architectural material for ground cover. Sorting also makes it useful as a road-building material. Its soft-brittle nature allows it to be compacted into easily formed cinder blocks. Block-quality cinder is apparently limited to the fields mentioned above; the pyroclastic cones of the other fields are too tightly welded or are composed of mixtures too heterogeneous to be economically useful.

The less common types of monogenetic volcanoes are the most interesting. Cinder cones represent the greatest degree of basalt disruption; lava cones constitute the other extreme—they are low, broad, shield-shaped cones constructed by effusion of liquid lava without production of significant scoria (fig. 7). All the cones in the Sentinel Plain and most in the Moctezuma fields are of this type. Several large lava cones are located in the vicinity of St. Johns in the Springerville field. Spatter cones and spatter ramparts, piles of welded blobs around vents or along fissures, occur in Pinacate where low-viscosity lava blobs were ejected gently from conduits.

Maar craters and tuff rings are special types of monogenetic volcanoes, products of "hydro-volcanic" processes where the magma mixed mechanically with water (ground water in this region) to generate steam explosions. Maar craters like those of Pinacate are among the most spectacular volcanic landforms in North America (fig. 8). Hydro-volcanism is a chance phenomenon; hydro-volcanic features are commingled in both space and time with normal, strombolian volcanoes. Hydro-volcanic processes have been studied by experimentation with thermite and water (Sheridan and Wohletz, 1983; Wohletz and Sheridan, 1983), but the mechanism by which magma-water interactions become established remains enigmatic. Hydro-volcanic phases apparently occur during otherwise normal strombolian eruptions.

Hydro-volcanic eruptions produce two distinctive volcanic landforms, a constructional tuff cone or a tuff ring and an excavated maar crater. The tuff produced by interaction of basalt magma and water is tan to yellowish, composed of a mixture of crystal shards with accidentally included fragments of the underlying country rock and alluvium, in a matrix of hydrated basaltic glass. Beds of tuff commonly have the characteristic sedimentary bed forms of a high-energy depositional environment (Crowe and Fisher, 1973). These beds are called "base-surge" beds because they were deposited from a cloud that exploded vertically out of the eruption site and then spread radially outward after falling back toward the vent. A maar crater is a destructional

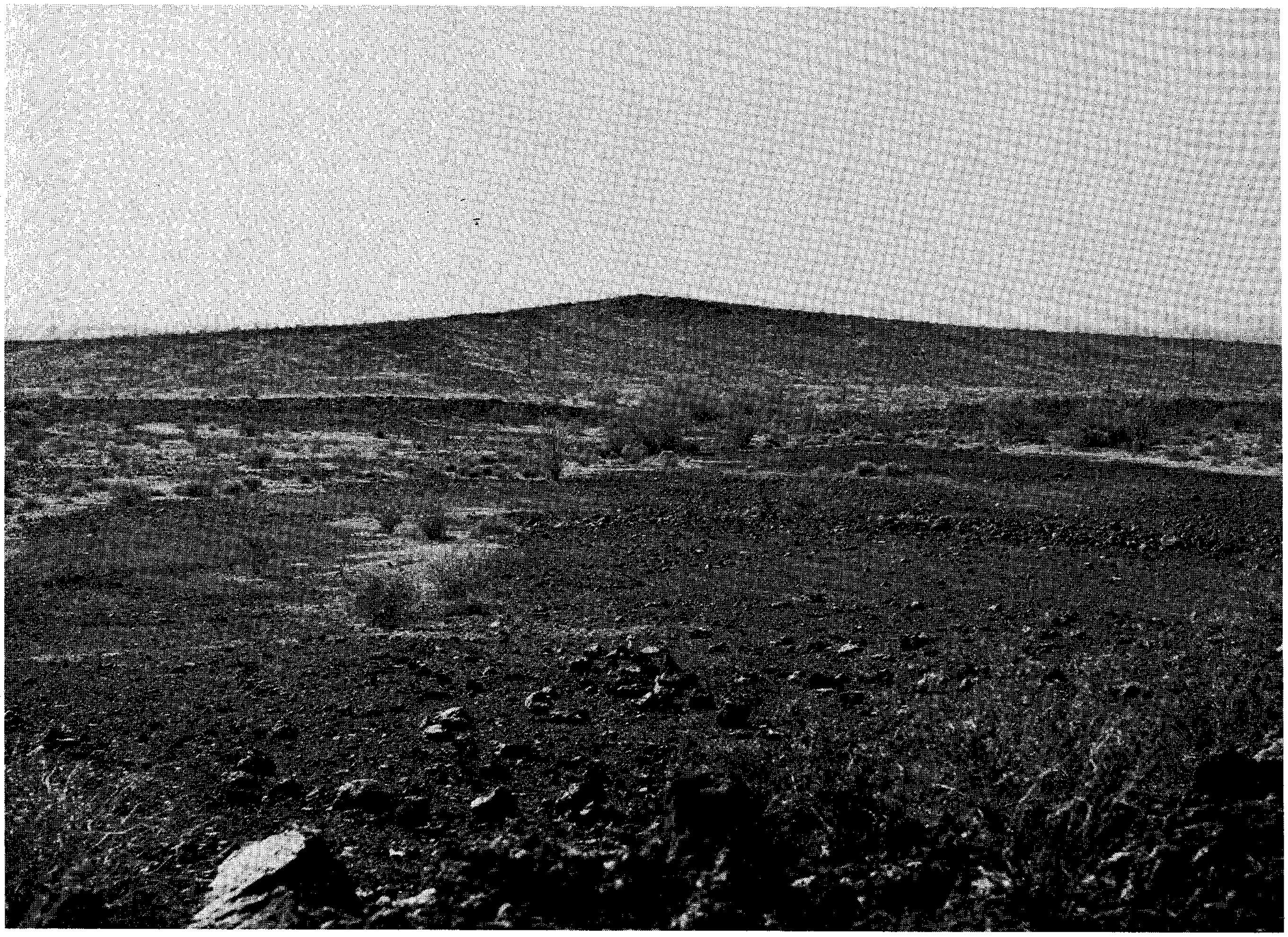

Figure 7. A Sentinel Plain lava cone. The 5° slopes of this cone are the result of fluid lava flowing out of the central conduit and spreading radially outward, without significant pyroclastic activity. D. Lynch photo.

landform, a depression excavated by the forces of eruption. Its final form is usually the result of post-eruptive collapse of the walls into the crater (Gutmann, 1976).

Cone erosion depends on the variables of internal welding, climate, and time. As might be expected, solid lava cones are most persistent; some essentially unmodified lava cones of mid-Neogene age have been identified in the state (Sheridan, 1984; Suneson and Lucchitta, 1979). Pyroclastic cones are relatively easily eroded, but the course of erosion is not simple. At first, even the loosest cinder cone is indestructible because any rain that falls on its slopes is immediately absorbed and, without runoff, erosion is impossible. Only after the surface has been plugged by weathering of the cinder (Colton, 1967) or by accumulation of dust and sand (Lynch, 1981) can runoff form rills and gullies. However, grass and other vegetation may grow as soil either forms or accumulates (if the climate is suitable), and this retards runoff, preventing erosion of gullies.

Wood (1980) proposed that the movement of loose material downslope should be an orderly, time-dependent process that lowers cone heights and expands base diameters so that the ratios of base to height increase as a simple, linear function of age (rates vary from field to field). "Morphometric degradation analysis" yielded reasonable age approximations in the San Francisco and several other volcanic fields (Wood, 1980). Cone erosional shape is clearly age dependent, but objective criteria of measurable morphology are only rarely useful as indicators of absolute age; most investigators use relative criteria of appearance groups (Colton, 1967).

In the grass-covered Springerville field, which has cones much older than Pinacate (Condit, 1984; Lynch, 1981), most of the cones are rounded hills lacking gullies or other sharp relief. Cone slopes connect with the surrounding flat land across concave talus ramparts (like those seen in figure 6) on all but the youngest cones. In contrast, cones of

Figure 8. Maar craters and tuff rings of Pinacate. The grey tuff ring of Grande maar (Sykes Crater), in the foreground, rests atop fresh lava and remnants of a cinder cone (visible in the far wall) that were constructed in the strombolian phase of this same eruption. Hydro-volcanic explosions that excavated the maar and created the tuff, began when ground water gained access to the magma. In the far distance is MacDougal maar crater, a similar volcanic feature. D. Lynch photo.

Pinacate are mostly of sharp relief with steep, cliffy sides and a mixture of talus rampart and sharp-angular bases (see fig. 3). Erosionally effective rainfall in both fields commonly comes from violent convective storms that generate runoff having prodigious carrying power. Grass in the Springerville field retards runoff and slows transport of the cinder. On the bare Pinacate cones, detritus is not only swept down the sides but is also removed from the cone bases.

Off-road vehicles have killed the grass in tracks made straight up the sides of many cones in the Springerville and

San Francisco fields. Gullies, some nearly a meter deep after only a few years, are forming on the otherwise uneroded cones.

THE LAVA FLOWS

Relationships between pyroclastic cones and their accompanying lava flows are rarely simple. At a few cones, like SP in figure 6, the lavas appear to have issued from the bases of cone walls, and the walls are unbroken. But most Arizona cones are breached: the cone walls have been carried away on the lava flow (see fig. 3). Breaching can result from effusion of lava into a crater, filling it with a lake of dense liquid which presses outward and causes the weakest section of cone wall to fail.

Although most recently observed strombolian eruptions began with a cinder eruption that built a cone and was followed by outflow of lava, Gutmann (1979) found evidence in Pinacate that cone-building pyroclastic activity was a second phase after initial effusion of lava. Many Pinacate cone walls were constructed atop liquid lava that flowed beneath the weight of the accumulating wall, causing both the lava surface and the overlying tephra deposits to deform simultaneously. Wall failure was common in Pinacate because wall deposits accumulated atop the lava flows that eventually carried them away (Gutmann, 1979).

Figure 9. Classic pahoehoe—smooth, glassy skin and ropy banding are characteristic of this surface. Here, one slab of solid surface detached from the underlying liquid and was thrust over an adjacent slab (Ives flow, Pinacate field). D. Lynch photo.

Pahoehoe lava surface is rare in Arizona fields; a few of the Pinacate flows (fig. 9) and the McCartys flow of the Zuni-Bandera field are the only occurrences. A considerable variation is found among surfaces in the rough "aa" category (fig. 10). Aa is usually scoriaceous, spiny, rough, and irregular to a microscopic scale. The most common surface arrangement is loose and unstable blocks with some spires locked in place. A few aa lava surfaces are "slab-chaos," jumbles of broad, thin slabs, some of which may have pahoehoelike texture on one side (fig. 11).

The much-photographed lava flow that extends northward from SP Crater has a rough, "block lava" surface (fig. 12) composed of non-spiny, non-scoriaceous clasts. Block lava is a primary surface type, like aa and pahoehoe, generated by brittle fracture deformation of the viscous flowing lava. Basalt will weather and erode to form blocky rubble that may look like block lava, but it is usually surrounded by soil and is of much more heterogeneous clast size.

Lava flow surfaces degrade initially by infilling. If the rough surface is not covered with cinder of its own or of a subsequent eruption, the roughness "spoils" (in an aerodynamic sense) the wind flow, making the lava an effective trap for airborne dust or sand. This eolian material is carried by rain into the fine fractures of the rock where it contributes to rock disintegration (Dohrenwend and others, 1984). Clay-hydration wedging and growth of salt crystals are warm-desert equivalents of frost wedging that operates in the colder areas of Arizona. As both airborne and rock-disintegration detritus accumulates, flow-surface irregularities are buried and plants move in. Grass and shrubs catch airborne dust as well as lava spines, and the roots accelerate disintegration.

CONCLUSIONS, SPECULATIONS, AND THE FEAR OF FIRE

Recognizable alkali basalt volcanoes, cinder cones mostly, occur clustered in discrete volcanic fields in all the major geologic provinces of Arizona. Petrologic, trace-element, and isotopic studies show that the magmas were generated in the upper mantle below the effects of crustal tectonics. Considering the similarities of rock compositions and eruption types (as reflected in the similarity of landforms), all the Plio-Pleistocene volcanic fields in the region should have a similar origin. The close spacing of volcanoes in the fields and the wide spacing between

Figure 10. Classic aa lava—The surface is composed of loose clasts with spiny exteriors that "clink" together when disturbed (Carnegie east flow, Pinacate field). D. Lynch photo.

volcanic fields rule out tapping of a generally available magma supply in the upper mantle through special crustal weaknesses. Volcanic fields on the surface show the locations of magma sources beneath the crust. Because magma transport through the crust is essentially vertical, the areal extent of the source is probably no larger than that of the active field.

The basalt magma sources are either volumes of mantle rock in rising diapirs that are melting as the pressure decreases (Maaloe and Johnson, 1985; O'Hara, 1985) or volumes of mantle rock being heated and perhaps metasomatized by plumes of heat-transporting volatiles (Anderson, 1981; Menzies and others, 1985). Nothing so far identified in rock composition or volcano distribution can identify the *true* source. Conventional wisdom leads us to expect effects other than volcanism from the rise of large masses of mantle rock, things like regional uplift or at least telltale gravity anomalies.

Best and Brimhall (1974) proposed a plume to account for the volcanism in Uinkaret, but they attributed the partial melting to the effects of "localized shear heating." Tanaka and others (1986) also appealed to shear heating to provide magmas in the San Francisco field. Their model involves local acceleration of flow in the asthenosphere around a "bump" on the base of the lithosphere to provide heat through viscous dissipation effects. Lateral flow in the asthenosphere is important to their model to explain the eastward migration of the center of volcanic activity.

My prejudice has been for plumes of volatiles from beneath the shallow mantle (Lynch, 1981, 1984). Menzies and others (1985) pointed out the importance of volatile-transfer processes along with magma injection for metasomatizing the mantle beneath the Geronimo (San Bernardino) field, but they left unspecified the ultimate source of magmas or the volatiles.

The distribution pattern of volcanic fields defined by Smith and Luedke (1984) may show structures in the subasthenospheric mantle that influence the magma sources. Alternatively, the sources may be randomly scattered, and the pattern comes from our human desire to

Figure 11. Slab chaos—This is a transitional surface type generated where pahoehoe slabs were disrupted and jumbled by a change of flow regime within the moving lava (Baroque flow, Pinacate field). D. Lynch photo.

find or impose order. Some plumes may be like bubbles that rise into the upper mantle and produce magmas for only a short time, leaving fields like Sentinel Plain with a limited range of rock ages. Others may be long-lived, fixed features of the mantle, "painting" stripes of volcanic fields atop the lithosphere (Vink and others, 1985). The migration of volcanism at Uinkaret (Best and others, 1980) and at San Francisco (Tanaka and others, 1986) may in fact record westward or southwestward movement of the North America plate that is somehow not reflected in volcano distribution in other fields. Alternatively, the locus of magmatism may have shifted in these two places.

Many questions remain. Eruption of alkali-basalt magma in a desert setting has never been observed; the possible courses of such eruptions can only be inferred from other eruptions in other places of other magma types. Are the desert eruptions singular and continuous, or have they several phases separated by long time breaks? If eruptions are multiphase, how are the conduits preserved? Hydrovolcanic eruptions have been observed where magma has been able to interact with sea or lake water, but never with ground water. What are the circumstances by which such interactions get started? Is it possible that the magmas of maar crater-tuff ring eruptions are atypical, different somehow from the alkalic magmas of the other volcanoes in the field?

The analytical data base of Arizona volcanic rock is woefully inadequate. Almost all of the late Neogene volcanic rock is alkali olivine basalt but AOB is not restricted to this time period. Sheridan and Nealey (this volume) report AOB in many volcanic fields of Oligocene and Miocene age as part of bimodal basalt-rhyolite suites. How was genesis of these older magmas related to genesis of the late Neogene alkali basalt magmas? If all alkali basalts are generated by mantle plumes, were plumes involved with subduction-related Mid-Tertiary magma genesis?

One final concern is Arizona volcanism as a geologic hazard. In those fields showing evidence of eruptions within the past few thousand years—Uinkaret, Pinacate and San

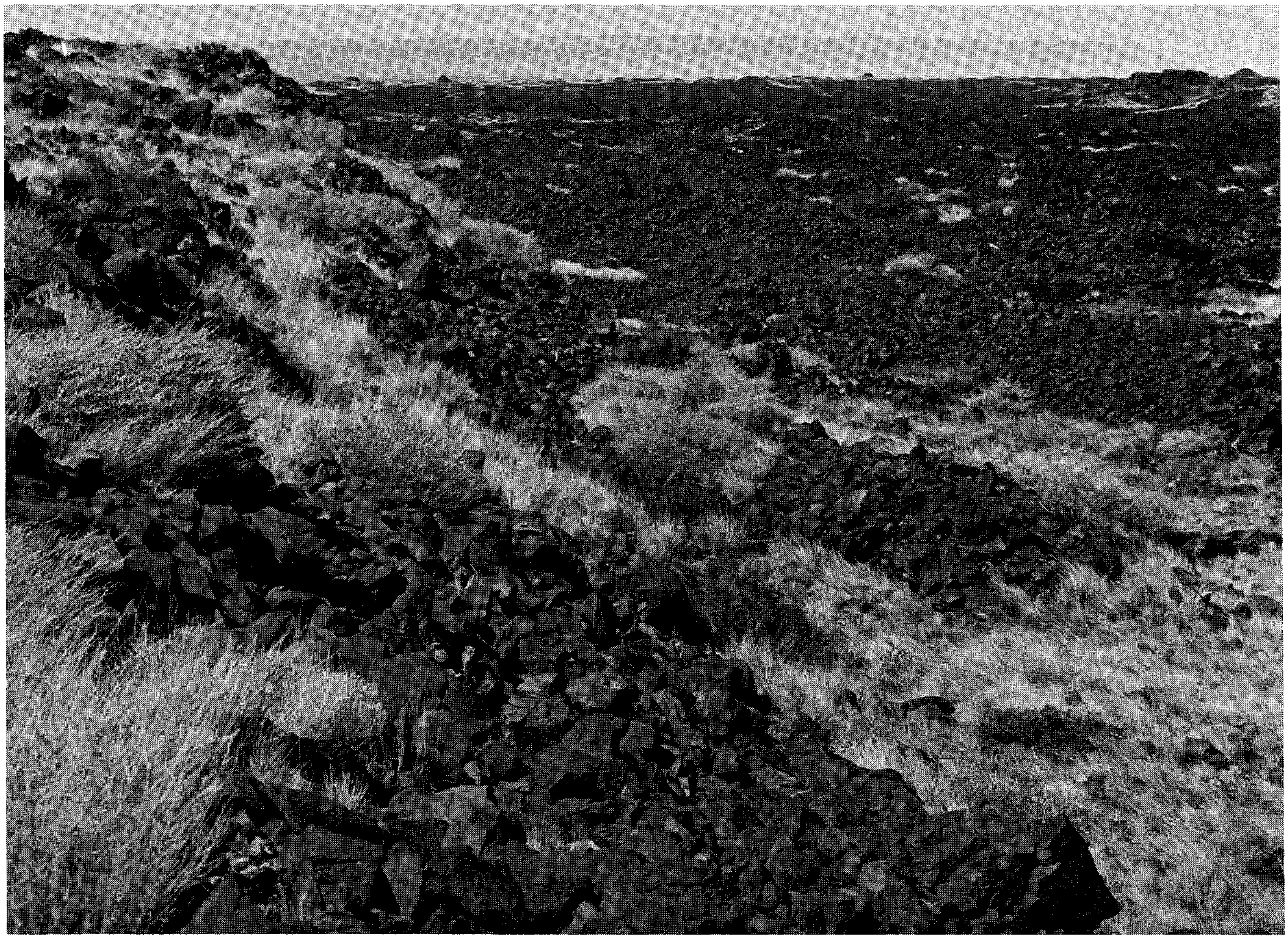

Figure 12. Block lava—The surface of the SP lava is primary, not the result of erosion. The blocks have smooth fracture faces but are arrayed like clasts in the aa of figure 10. (SP flow, San Francisco field). D. Lynch photo.

Francisco—future activity is almost assured. The first two fields are in uninhabited desert, so activity in either will be no more than spectacle unless the eruption happens to cut a major highway; even that will not constitute a disaster.

The city of Flagstaff lies within the boundaries of the San Francisco field and is growing toward the part of the field that has had the most recent activity. Explosive eruption of high-silica magma is highly unlikely but not completely impossible in the San Francisco field. But even a low-energy strombolian eruption would cause considerable property damage and social disruption. A cinder eruption like Sunset Crater could blanket the entire city and cut both a major railroad and interstate highway.

Considering the actions of the Flagstaff citizens, fear of volcanic eruption is not a major concern, nor should it be. The computed average recurrence intervals for strombolian eruptions in the San Francisco field is 3,000 years (Tanaka and others, 1986), the same as Pinacate (Lynch, 1981). Volcanic eruptions are spectacular and sometimes devastating; they always capture public interest. For Arizonans, however, the hazards of flood and earthquake are more immediate.

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REFERENCES

Allmendinger, R. W., Hauge, T. A., Hauser, E. C., Potter, C. J., Klemperer, S. L., Nelson, K. D., Knuepfer, S. L., Oliver, J., 1987, Overview of the COCORP 40°N transect, western United States: the fabric of an orogenic belt: Geological Society of America Bulletin, v. 98, p. 308-319.

Ander, M. E., Heiken, G., Eichelberger, J., Laughlin, A. W., and Huestis, S., 1981, Geological and geophysical investigations of the Zuni-Bandera volcanic field, New Mexico: Los Alamos Scientific Laboratory Report LA 8824MS/VC66B, 33 p.

Anderson, D. L., 1981, Hotspots, basalts and the evolution of the mantle: Science, v. 213, p. 82-89.

Arndt, N. T., 1977, The separation of magmas from partially molten peridotite: Carnegie Institution of Washington Yearbook 1976, p. 424-428.

Best, M. G., 1970, Kaersutite-peridotite inclusions and kindred megacrysts in basanitic lavas, Grand Canyon, Arizona: Contributions to Mineralogy and Petrology, v. 27, p. 25-44.

Best, M. G., and Brimhall, W. H., 1974, Late Cenozoic alkali basaltic magmas in the western Colorado Plateau 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.

Best, M. G., McKee, E. H. and Damon, P. E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035-1050.

Blackburn, E. A., Wilson, L., and Sparks, R. S. J., 1976, Mechanics and dynamics of strombolean activity: Journal of the Geological Society of London, v. 132, p. 429-440.

Champion, D., 1980, Holocene geomagnetic secular variations in the western United States; implications for the global geomagnetic field: Menlo Park, California, U.S. Geological Survey Open-File Report 80-824, 326 p.

Colton, H. S., 1967, The basaltic cinder cones and lava flows of the San Francisco Mountain volcanic field: Museum of Northern Arizona Bulletin 10 [originally issued 1936], 58 p.

Condit, C. D., 1984, The geology of the western part of the Springerville volcanic field, east-central Arizona: Albuquerque, University of New Mexico, unpublished Ph. D. dissertation, 465 p.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-406.

Cox, K. G., Bell, J. D., and Pankhurst, R. J., 1979, The interpretation of igneous rocks: London, George Allen and Unwin Ltd., 450 p.

Crowe, B. M., and Fisher, R. V., 1973, Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California: Geological Society of America Bulletin, v. 84, p. 663-681.

Crumpler, L. S., Aubele, J. C., and Shafiqullah, M., 1986, K-Ar ages of late Cenozoic rocks of the central and eastern parts of the Springerville volcanic field, east-central Arizona: Isochron/West, no. 46, p. 3-5.

Damon, P. E., 1971, Relationships between late Cenozoic volcanism and tectonics and orogenic-epeirogenic periodicity, *in* Turekian, K. K., ed., Conference on the late Cenozoic glacial ages: New York, John Wiley and Sons, p. 15-35.

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* Karlstrom, T. N. V., Swann, G. A., and Eastwood, R. L., eds., Geology of Northern Arizona, Part 1—Regional studies: Flagstaff, Arizona, Geological Society of America Rocky Mountain Section Meeting, Guidebook, p. 221-235.

Damon, P. E., Shafiqullah, M., and Clark, K. F., 1981, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera: Tucson, Arizona Geological Society Digest 14, p. 137-154.

Dohrenwend, J. C., McFadden, L. D., Turrin, B. D., and Wells, S. G., 1984, K-Ar dating of the Cima volcanic field, eastern Mojave County, California: late Cenozoic volcanic history and landscape evolution: Geology, v. 12, p. 163-167.

Donnelly, M. F., 1974, Geology of the Sierra del Pinacate volcanic field, northern Sonora and southern Arizona, U. S. A.: Palo Alto, California, Stanford University, unpublished Ph. D. dissertation, 722 p., University Microfilms #75-6838.

Elders, W. A., and Beihler, S., 1975, The Gulf of California rift system and its implications for the tectonics of western North America: Geology, v. 3, p. 85-87.

Evans, S. H., and Nash, W. P., 1979, Petrogenesis of xenolith-bearing basalts of southeastern Arizona: American Mineralogist, v. 64, p. 249-267.

Fedotov, S. A., 1976, Ascent of basic magmas in the crust and the mechanism of basaltic fissure eruptions: International Geology Review, v. 20, p. 33-47.

Feigenson, M. D., Hoffmann, A. W., and Spera, F. J., 1984, Case studies in the origin of basalt II: the transition from tholeiitic to alkaline volcanism on Kohala Volcano, Hawaii: Contributions to Mineralogy and Petrology, v. 84, p. 390-405.

Fowler, A. C., 1985, A mathematical model of magma transport in the asthenosphere: Geophysical and Astrophysical Fluid Dynamics, v. 33, p. 63-91.

Frey, F. A., Green, D. H., and Roy, S. D., 1978, Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from southeastern Australia utilizing geochemical and experimental data: Journal of Petrology, v. 19, p. 463-513.

Frey, F. A., and Prinz, M., 1978, Ultramafic inclusions from San Carlos, Arizona: petrologic and geochemical data bearing on their petrogenesis: Earth and Planetary Sciences Letters, v. 38, p. 19-176.

Gast, P. W., 1968, Trace element fractionation and the origin of the tholeiitic and alakalic magma types: Geochimica et Cosmochimica Acta, v. 32, p. 1057-1086.

Gust, D. A., Arculus, R. J., Moore, R. B., Wolfe, E. W., and Ulrich, G. E., 1984, Mantle-derived magma interaction with crust and the development of hybrid alkali— calc-alkali lineages [abs.]: Geological Society of America, 97th Annual Meeting, Reno, Nevada, Abstracts with Programs, v. 16, no. 6, p. 526.

Gutmann, J. T., 1972, Eruptive history and petrology of Crater Elegante, Sonora, Mexico: Palo Alto, California, Stanford University, unpublished Ph. D. dissertation, 253 p., University Microfilms #72-20704.

Gutmann, J. T., 1976, Geology of Crater Elegante, Sonora, Mexico: Geological Society of America Bulletin, v. 87, p. 1718-1729.

Gutmann, J. T., 1979, Structure and eruptive cycles of cinder cones in the Pinacate volcanic field and controls on strombolean activity: Journal of Geology, v. 87, p. 448-454.

Hamblin, W. K., 1970, Structure of the western Grand Canyon region, *in* Hamblin, W. K., and Best, M. G., eds., The western Grand Canyon district: Utah Geological Society, Guidebook to the Geology of Utah, no. 23, p. 3-19 and Plate 1.

Harte, B., 1983, Mantle peridotites and process—the kimberlite sample, *in* Hawkesworthy, C. J., and Norry, M. J., eds., Continental basalts and their mantle xenoliths: Nantwitch, Cheshire, United Kingdom, Shiva Publishing Limited, p. 46-91.

Kempton, P. D., Dungan, M. A., and Menzies, M. A., 1982, Petrology and geochemistry of ultramafic xenoliths from the Geronimo volcanic field: Terra Cognita, v. 2, p. 222.

Laughlin, A. W., Brookins, D. G., Damon, P. E., and Shafiqullah, M., 1976, Late Cenozoic volcanism of the Jemez zone, Arizona-New Mexico: Isochron/West, v. 25, p. 5-8.

Laughlin, A. W., Brookins, D. G., Kudo, A. M., and Causey, J. D., 1971, Chemical and strontium isotopic investigations of ultramafic inclusions and basalt, Bandera Crater, New Mexico: Geochimica Cosmochimica Acta, v. 35, p. 107-112.

Leeman, W. P., 1970, The isotopic composition of strontium in late-Cenozoic basalts from the Basin-Range province, western United States: Geochimica et Cosmochimica Acta, v. 34, p. 857-872.

Leeman, W. P., 1974, Late-Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona: isotopic composition of strontium: Geological Society of America Bulletin, v. 85, p. 1691-1696.

Lynch, D. J., 1978, The San Bernardino volcanic field of southeastern Arizona, *in* Callender, J. F., Wilt, J. C., and Clemons, R. E., eds., Land of Cochise: Socorro, New Mexico Geological Society Twenty-ninth Field Conference Guidebook, p. 261-268.

Lynch, D. J., II, 1981, Genesis and geochronology of alkaline volcanism in the Pinacate volcanic field, northwestern Sonora, Mexico: Tucson, University of Arizona, unpublished Ph. D. dissertation, 248 p.

Lynch, D. J., 1984, A model for monogenetic volcanism in western North America: Geological Society of America Abstracts with Programs, 97th Annual Meeting, Reno, Nevada, v. 16, no. 6, p. 581.

Maaloe, S., and Johnson, A. D., 1986, Geochemical aspects of some accumulation models for primary magmas: Contributions to Mineralogy and Petrology, v. 93, p. 449-458.

Marsh, B. D., 1981, On the crystallinity, probability of occurrence and rheology of lava and magma: Contributions to Mineralogy and Petrology, v. 78, p. 85-98.

Marsh, B. D., and Maxey, M. R., 1985, On the distribution and separation of crystals in convecting magma: Journal of Volcanology and Geothermal Research, v. 24, p. 95-150.

McKenzie, D., 1984, The generation and compaction of partially molten rock: Journal of Petrology, v. 25, p. 713-765.

Menzies, M. A., 1983, Mantle ultramafic xenoliths in alkaline magmas: evidence for mantle heterogeneity modified by magmatic activity, *in* Hawkesworthy, C. J., and Norry, M. J., eds. Continental basalts and their mantle xenoliths: Nantwitch, Cheshire, United Kingdom, Shiva Publishing Limited, p. 92-110.

Menzies, M., and Rama Murthy, V., 1980, Mantle metasomatism as a precursor to the genesis of alkaline magmas—isotopic evidence: American Journal of Science, v. 280-A, p. 622-638.

Menzies, M. A., Kempton, P., and Dungan, M., 1985, Interaction of continental lithosphere and asthenospheric melts below the Geronimo volcanic field of Arizona, USA: Journal of Petrology, v. 26, p. 663-693.

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.

Nakamura, K., 1977, Volcanoes as possible indicators of tectonic stress orientation, principle and proposal: Journal of Volcanology and Geothermal Research, v. 2, p. 1-16.

Norry, M. J., and Fitton, J. G., 1983, Compositional differences between oceanic and continental basic lavas and their significance, *in* Hawkesworthy, C. J., and Norry, M. J., eds., Continental basalts and their mantle xenoliths: Nantwitch, Cheshire, United Kingdom, Shiva Publishing Limited, p. 5-19.

O'Hara, M. J., 1985, Importance of the "shape" of the melting regime during partial melting of the mantle: Nature, v. 314, p. 58-61.

Paz-Moreno, F. A., 1984, Composicion y origen de los basaltos (malpais) Plio-Cuaternarios de Moctezuma, Sonora, Mexico: Sociedad Geologica Mexicana Memorias VII, p. 95-104 [in Spanish].

Potter, C. J., Char-Shine, L., Jiazheng, H., Li, Z., Hauge, T. A., Hauser, E. C., Allmendinger, R. W., Oliver, J. E., Kaufman, S., and Brown, L., 1987, Crustal structure of north-central Nevada: results from COCORP deep seismic profiling: Geological Society of America Bulletin, v. 98, p. 330-337.

Ragland, P. L., and Rogers, J. W. W., eds., 1984, Basalts: New York, Van Nostrand and Reinhold, Benchmark papers in geology, Vol. 71, 430 p.

Reches, Z., 1978, Analysis of faulting in three-dimensional strain field: Tectonophysics, v. 47, p. 109-129.

Reches, Z., 1983, Faulting of rocks in three-dimensional strain fields: II. Theoretical analysis: Tectonophysics, v. 95, p. 133-156.

Ringwood, A. E., 1975, Composition and petrology of the Earth's mantle: New York, McGraw-Hill, 618 p.

Roberts, J. L., 1970, The intrusion of magma into brittle rocks, *in* Newall, G., and Rast, W., eds., Mechanism of igneous intrusion: Liverpool, England, Gallery Press, p. 287-336.

Schwarzer, R. R., and Rogers, J. W. W., 1974, A worldwide comparison of alkali olivine basalts and their differentiation trends: Earth and Planetary Sciences Letters, v. 23, p. 286-296.

Shoemaker, E. M., Squires, R. L., and Abrams, M. J., 1978, Bright Angel and Mesa Butte fault systems in 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.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Tucson, Arizona Geological Society Digest 12, p. 201-260.

Sheridan, M. F., 1984, Volcanic landforms, *in* Smiley, T. L., and others, eds., Landscapes of Arizona: the geologic story: Lanham, Maryland, University Press of America, p. 175-206.

Sheridan, M. F., and Wohletz, K. H., 1983, Hydrovolcanism: basic considerations and review: Journal of Volcanology and Geothermal Research, v. 17, p. 1-29.

Smiley, T. L., 1958, Geology and dating of Sunset Crater, Flagstaff, Arizona, *in* Anderson, R. Y., and Harshbarger, J. W., Guidebook of the Black Mesa Basin, northeastern Arizona: Socorro, New Mexico Geological Society, 9th Field Conference, p. 186-190.

Smith, R. L., and Luedke, R. G., 1984, Potentially active volcanic lineaments and loci in the western conterminous U.S., in Explosive volcanism: inception, evolution and hazards, *in* Studies in geophysics of the National Research Council: Washington, D. C., National Academy Press, p. 47-66.

Sparks, R. S. J., 1978, The dynamics of bubble formation and growth in magmas: a review and analysis: Journal of Volcanology and Geothermal Research, v. 3, p. 1-37.

Suneson, N. H., and Lucchitta, I., 1979, K-Ar ages of Cenozoic volcanic rocks in west-central Arizona: Isochron/West, v. 24, p. 25-29.

Tanaka, K. L., Shoemaker, E. M., Ulrich, G. E., and Wolfe, E. W., 1986, Migration of volcanism in the San Francisco volcanic field, Arizona: Geological Society of America Bulletin, v. 97, p. 129-141.

Terrell, D. J., Pal, Surendra, Lopez M., Margarita, and Perez R., Jose, 1979, Rare earth elements in basalt samples, Gulf of California: Chemical Geology, v. 26, p. 267-275.

Vink, S. E., Morgan, J., and Vogt, P. R., 1985, The Earth's hot spots: Scientific American, v. 252, no. 4, p. 50-57.

Wass, S. Y., and Rogers, N. W., 1980, Mantle metasomatism— precursor to continental alkaline volcanism: Geochimica et Cosmochimica Acta, v. 44, p. 1811-1824.

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

Wilshire, H. G., and Shervais, J. W., 1975, Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks of the western United States: Physics and Chemistry of the Earth, v. 9, p. 83-98.

Wilson, E. D., 1962, A résumé of Arizona geology: Tucson, Arizona Bureau of Mines Bulletin 171, 140 p.

Wilson, Lionel, and Head, J. W., III, 1981, Ascent and eruption of basaltic magma on the Earth and Moon: Journal of Geophysical Research, v. 86, p. 2971-3001.

Wohletz, K. H., and Sheridan, M. F., 1983, Hydrovolcanic explosions II: evolution of basaltic tuff rings and tuff cones: American Journal of Science, v. 283, p. 85-413.

Wolfe, E. W., 1984, The volcanic landscape of the San Francisco volcanic field, *in* Smiley, T. L., and others, eds., Development of the Arizona landscape: the geologic story: Lanham, Maryland, University Press of America, p. 111-136.

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

Wood, C. A., 1980, Morphometric evolution of cinder cones: Journal of Volcanology and Geothermal Research, v. 7, p. 387-431.

Yoder, H. S., 1976, Generation of basaltic magma: National Academy of Science, Washington, D. C., 265 p.

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