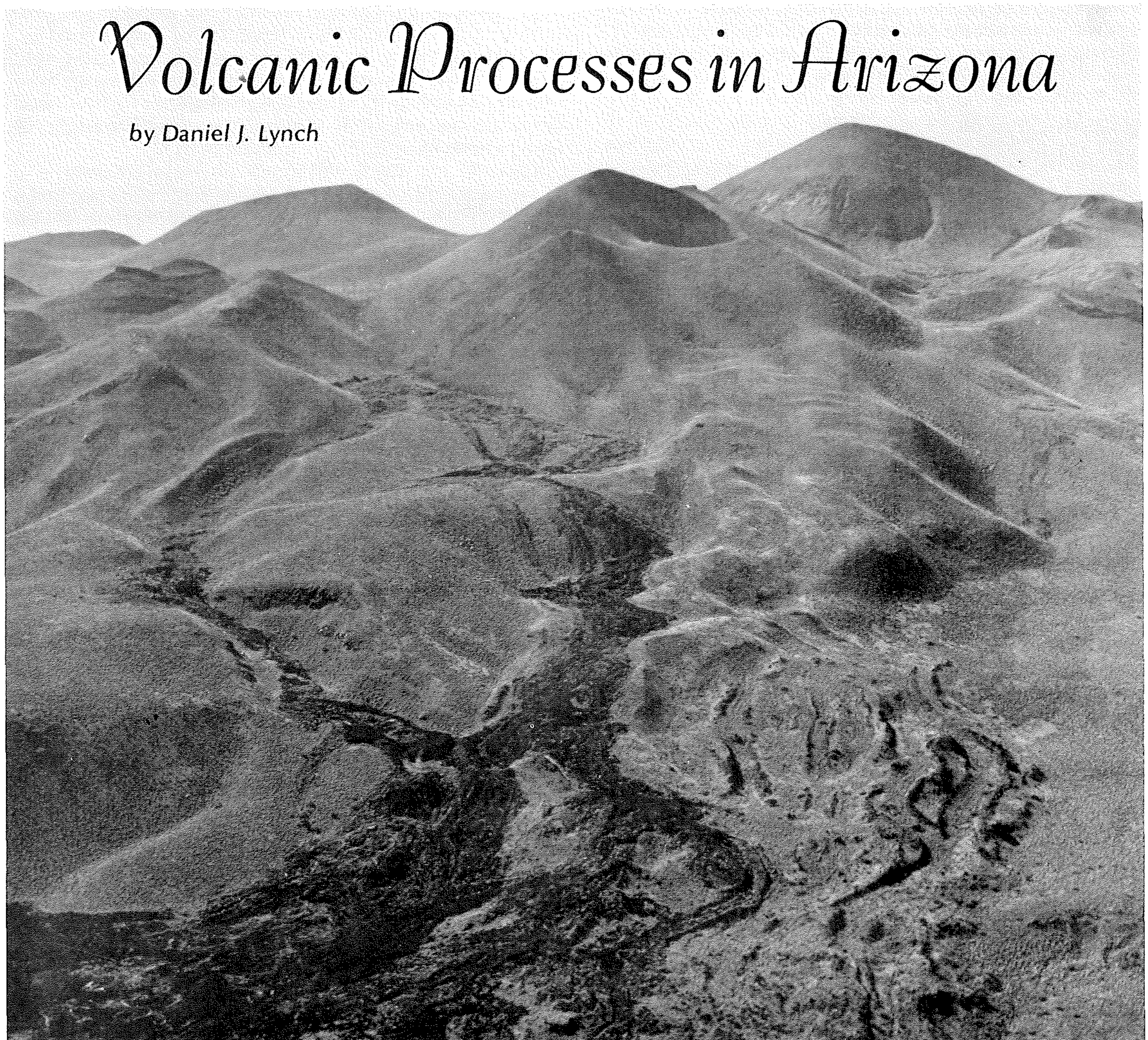
FIELDNOTES

From The Arizona Bureau Of Geology And Mineral Technology

Volume 12 No. 3 | Earth Sciences and Mineral Resources in Arizona | September 1982

Volcanic Processes in Arizona

by Daniel J. Lynch



All photographs in this article were taken by D.J. Lynch, except where noted.

Carnegie Cone in Pinacate. This relatively young pyroclastic cone, constructed on the edge of the Volcan Santa Clara summit platform, has a variety of typical and some unique features. Its last lava flows (center and left), erupted from a fissure at the base of the cone after cinder production had stopped; it has a pahoehoe surface above the slope break and a clinkery aa surface below it. The cinder-covered flows on the lower right were probably erupted before, and perhaps during, the cone construction. Directly above them is a hummocky debris flow which was once the northern wall of the cone. This wall was partially rebuilt after its collapse. Both the earlier and later lava flows have lava levees where the outer part of the flow congealed from cooling and the hot, liquid interior continued to move downslope. Behind Carnegie to the right is a wall of the whitish trachyte of Santa Clara, one of the most differentiated alkaline rocks in the region.

Volcanoes have been an important part of Arizona's geologic story since the state's first rocks were formed almost 2 billion years ago. Rocks of volcanic origin constitute nearly a third of the bedrock area, as depicted on the geologic map of Arizona.* These lava rocks are hard and persist as part of the geologic record for billions of years; but the volcanoes—those hills and mountains built around vents from the interior by the eruptions of molten lava and gas—are fragile and are usually destroyed by erosion in only a few millions of years. For this reason, Arizona has few volcanoes (recognizable landforms of volcanic construction) relative to its vast areas of volcanic rock and these landforms are almost all younger than 6 million years. The following narrative is a brief explanation of some of the processes that created these young volcanoes.

VOLCANIC FIELDS OF ARIZONA AND ITS BORDERLANDS

Figure 1 shows the distribution of Plio-Pleistocene age (younger than 6 million years) volcanic rock in Arizona. The areas depicted are actually fields of volcanoes and lava flows. Two things seem obvious from this map: the volcanism was not widely distributed across the state but was restricted to small and limited areas, and the location of these "volcanic fields" appears to bear no simple relationship to the geologic province boundaries. From this, it has been inferred by the writer that magma genesis is localized and that the processes responsible for the differences between geologic provinces have had little or no effect on the sites of magma generation.

Geologic Map of Arizona*, **prepared by the Arizona Bureau of Geology and Mineral Technology and the U.S. Geological Survey (1969).

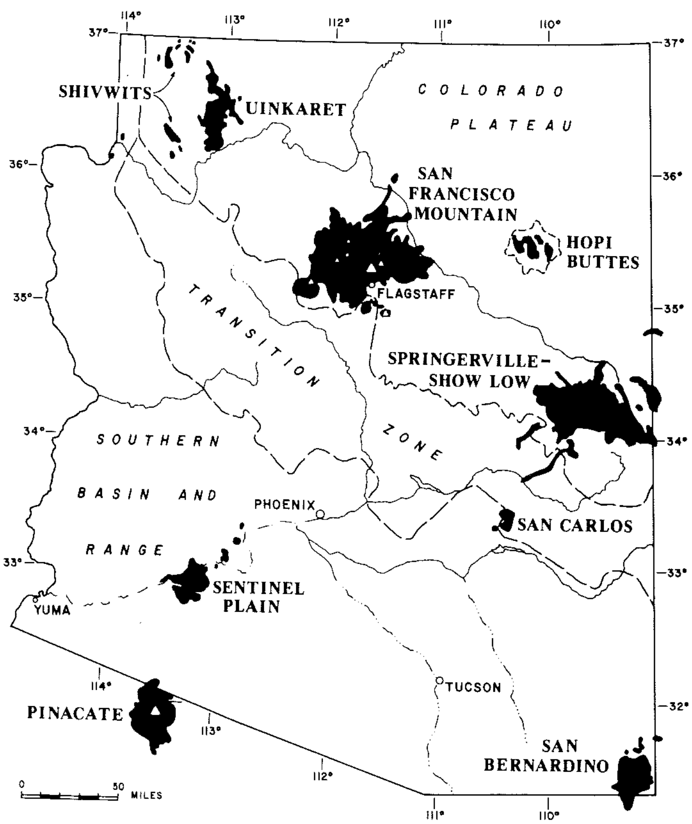


Figure 1. Distribution of Plio-Pleistocene age volcanic rocks in Arizona and its borderlands. Each of the areas depicted is a field of volcanoes and lava flows, erupted within the past 6 million years. Triangles indicate composite, polygenetic volcanic mountains.

The most obvious criterion for classifying young volcanoes is size—Arizona has large volcanic mountains and small volcanic hills. These volcanoes are different in many aspects other than size because of the effects that magma composition has on mode of eruption and volcano size. Lava that erupts from a volcano is called magma while it is still within the earth. Arizona's small volcanoes are monogenetic, that is, each was the product of a single eruption which probably lasted no more than a few months. The large volcanic mountains—composite, polygenetic volcanoes—are found in only two of the area's volcanic fields, Pinacate (primarily in northern Sonora, extending into southern Arizona), and San Francisco Peaks, along with the smaller volcanic hills. These large volcanoes were created by successive eruptions through the same conduit over time periods approaching a million years.

Rocks in the small volcanoes are mainly basalts in a limited compositional range whereas rocks of the large volcanoes are part of rock series of differing but related compositions. Higher rocks in each series are, in a sense, direct descendants of the rocks below. This relationship demonstrates systematic changes in the magmas that were erupted to construct the volcanoes. Beneath each volcano is the magma generating, transport, and storage system which ultimately determines the size and shape of that volcano. A volcanologist considers this system to be the most important part of the volcano because it is a window into the interior of the earth.

Lava rocks occur in a wide variety of compositional types. Two of the most important compositional variables are silica (SiO_2) and the sum of the alkalies ($Na_2O + K_2O$). See Figure 2. Different rock types can be distinguished using these criteria alone, although the definition of each type depends on many more variables. The diagram shows the two main differentiation trends, each of which starts with a different type of basalt magma (Figure 2).

THE SOURCE OF MAGMA

The parental magma of Arizona's volcanoes, large and small, is basaltic. Basalt magma is generated in the mantle, the layer beneath the crust, where rock is heated sufficiently to break the bonds which hold atoms in crystal lattices. Once bonds are broken, the loose atoms form a sort of "ionic soup" which is capable of flowing through cracks in the rock. The most probable source of Arizona's basaltic magma is peridotite, a rock composed mainly of olivine and pyroxene at depths greater than 50 kilometers in the mantle. In this environment, both temperature and pressure are high. Heat causes the ions to vibrate vigorously in their crystal lattices, but the pressure serves to hold them in place. Melting can occur either when heat is added or pressure is reduced. Growing evidence indicates that most basaltic magmas are generated by plumes of water and carbon dioxide diffusing into the upper mantle from beneath. The water and carbon dioxide become "volatile" constituents of the magma and, because they are mostly excluded from the structures of crystallizing minerals, they readily escape from the magma as gas during an eruption.

When melting occurs, the first-formed liquid is relatively rich in these volatiles and in elements of large ionic radius (Na, K, Rb, Zr for example) which do not fit particularly well

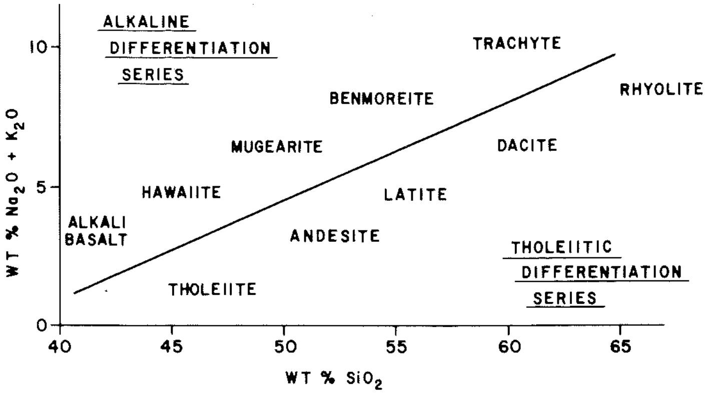


Figure 2. Volcanic rock names relative to contents of silica and alkali oxides for the two differentiation trends found in Arizona composite, polygenetic volcanoes.

into the tight lattices of mantle minerals. As melting progresses, smaller ions such as iron, calcium, and magnesium, along with silicon-oxygen groups, are added to the liquid, diluting concentrations of the other constituents. By this mechanism, the composition of the "primary" magma is controlled by the percentage of the source rock that partially melts. Most petrologists agree that alkali basalts arise from 5-10 percent partial melting and tholeiites (the common basalts of flood basalt provinces such as the Columbia Plateau) are generated by 15-25 percent partial melting in the mantle.

DIFFERENTIATION AND THE COMPOSITE VOLCANO TYPE

Stresses in the mantle-source region force the liquid out of cracks between mineral grains and collect it into a coherent, movable body which rises slowly. Magma in this body remains liquid at high temperature because bonds between ions cannot form, or those that do form are short lived. As the magma body rises toward the surface and cools, different kinds of bonds become permanent as the temperature changes and crystals form in the melt. The strongest bonds, those in high-melting point minerals like olivine and pyroxene, form first, and the less energetic bonds of the feldspars form later at lower temperatures. With only minor cooling after rising away from the source zone, most magmas become a crystal-liquid "stew" and, on eruption, yield a rock which is porphyritic, composed of large crystals (phenocrysts) in a matrix of small crystals formed of the rapidly cooled liquid.

In the magma chamber (the space occupied by the magma body), heavier crystals sink out of the magma. This process of "fractional crystallization" removes some elements, like iron and magnesium, and increases the concentrations of other elements in the remaining liquid (notably silica and the alkali elements, sodium and potassium) thereby changing the composition of the magma. Because this process depends on time and heat, a small body of magma is likely to change little from its primary composition before a single eruption exhausts it. A large magma body can feed several eruptions over a long period of time as the composition of the magma changes. Each successive eruption produces lava of a composition different from the one before and the compositions follow the trends illustrated in Figure 2.

Arizona's composite volcanic mountains (the big ones) were created above large magma bodies by numerous eruptions as the magma compositions changed through fractional crystallization. Volcan Santa Clara in Pinacate has all the members of the alkaline differentiation series with basalt (the most primitive) at the bottom and trachyte (the most differentiated) at the top. The San Francisco Mountain volcanic field (see Figure 3) is much more complex

Figure 3. The San Francisco Mountain, seen from the southwest. This volcano (a composite, polygenetic volcanic mountain), like its counterpart Santa Clara in the Pinacate field, was constructed by successive eruptions from a differentiating magma beneath it over nearly a million year time period. Also like Santa Clara, it is surrounded by a field of monogenetic volcanoes. Photo: Ed Wolfe (USGS).

than Santa Clara. There are several centers of differentiated volcanism on the largest mountain, and the lavas appear to have come from several different magma batches, possibly differentiating sequentially in the same site. The magmas in the two different volcanic fields followed different paths of fractionation because the primary magma was generated by different degrees of partial melting and, perhaps also, because the sites of fractionation were at different depths.

The compositional change on differentiation that most affects the mechanical behavior of the magma is the relative increase of silica. Semipermanent bonds form between the silicon-oxygen tetrahedra (the basic building blocks of silicate minerals) to create long chain polymers which increase the viscosity of the melt. Silica-poor magmas, like basalt, have many iron or magnesium ions that combine with the silica to prevent long chain polymers from forming. As differentiation progresses, iron and magnesium are removed and silicon is concentrated, improving the conditions for polymer formation and increasing the viscosity.

Magma viscosity controls both the ability of the magma to flow through the conduit and on the surface, as well as effecting the magma's explosivity. Highly viscous magmas show plastic or sometimes brittle behavior as they move, and they do not permit dissolved volatiles to escape easily. On eruption, if the volatile content is not excessive, these lavas tend to break into angular fragments and the "flows" move as glowing landslides and cool to become *agglomerate* (a volcanic rock which consists of welded, unsorted, angular fragments). Magmas of high-volatile content are torn into dust in "Plinian" style (named for the 79 A.D. eruption of Vesuvius, described by Pliny the Younger), highly explosive eruptions, amply illustrated one bright spring morning in 1980 at Mt. St. Helens. Large volcanoes are composite because they are fed by large magma bodies that are differentiating and producing progressively more viscous magmas. These volcanoes usually erupt a mixture of lava types from thick, pasty molten rock to agglomerate to dust and ash flows. Composite volcanoes are more likely to have explosive eruptions because of the differentiated, highly viscous magmas produced.

Figure 4. Eroded volcanoes in Pinacate. The large cone has the characteristic outward-facing cliff left when unconsolidated cinder is removed from the outer slope and more solid agglutinate remains on the inner slope. Festoon bands can be seen on the relatively young lava tongue in the foreground. Dunes of the Gran Desierto can be seen in the background west of the cone.

CINDER CONES AND KINDRED MONOGENETIC VOLCANOES

The monogenetic volcanoes are small pyroclastic cones (pyroclasts are fragments of fluid lava made by bursting gas bubbles) with thin lava flows dispersed across singular and discrete volcanic fields. They were created from small batches of magma which were collected at different times and in different places above a broad zone of magma production. Because the lavas of each volcano come from separate magma bodies, they are not directly related one to another, but are of similar composition because the processes of magma generation and early differentiation produce the same kind of rocks worldwide. The rocks are either basalts or lower members of differentiation series (lower left in Figure 2).

Volcano size is limited by the volume of magma available; the shape depends on the amount and mechanical behavior of gas escaping from the low viscosity lavas during the eruption. Gas escapes easily from fluid magmas as bubbles; therefore, eruptions are nonexplosive "strombolian" types, involving cinder jets, fire fountains, and extrusion of thin lava flows. The cinder jets and fire fountains construct cones of pyroclastic material around the vent mouth. Bubbles growing and bursting in the upper few-hundred meters of liquid in the vent tear the lava into a whole range of different kinds of pyroclastic material, depending on the amount and activity of dissolved gas escaping. Gas activity varies during an eruption because volatiles are not evenly distributed within an erupting magma batch. Usually the portion erupted first is volatile-rich and the volatile content decreases as the eruption progresses. However, this is not always the case; occasionally the first magma to reach the surface is volatile-poor, the eruption beginning with a lava flow.

High volatile content causes nucleation of numerous bubbles which grow by diffusion like the bubbles in soda pop. So many form that they eventually interfere with one another, stretching the otherwise low-viscosity magma into thin skins between bubbles. The resulting liquid-gas mixture has a high "kinematic viscosity", much like merengue on a lemon pie, and because it is brittle, it breaks into small, angular fragments—cinders. The larger cinders fall on the growing cone around the vent but the smaller ones become caught up in the rising gas cloud and may travel many kilometers downwind.

In portions of the magma containing less dissolved gas, the bubbles can grow by coalescence, because fewer form per unit time. The bursting of these larger bubbles in the vent mouth propels blobs of lava into the air. The blobs are larger and more dense than cinders and they are at least partially liquid. These flying, glowing blobs make up the fire fountains so picturesque in Hawaiian volcanic eruptions.

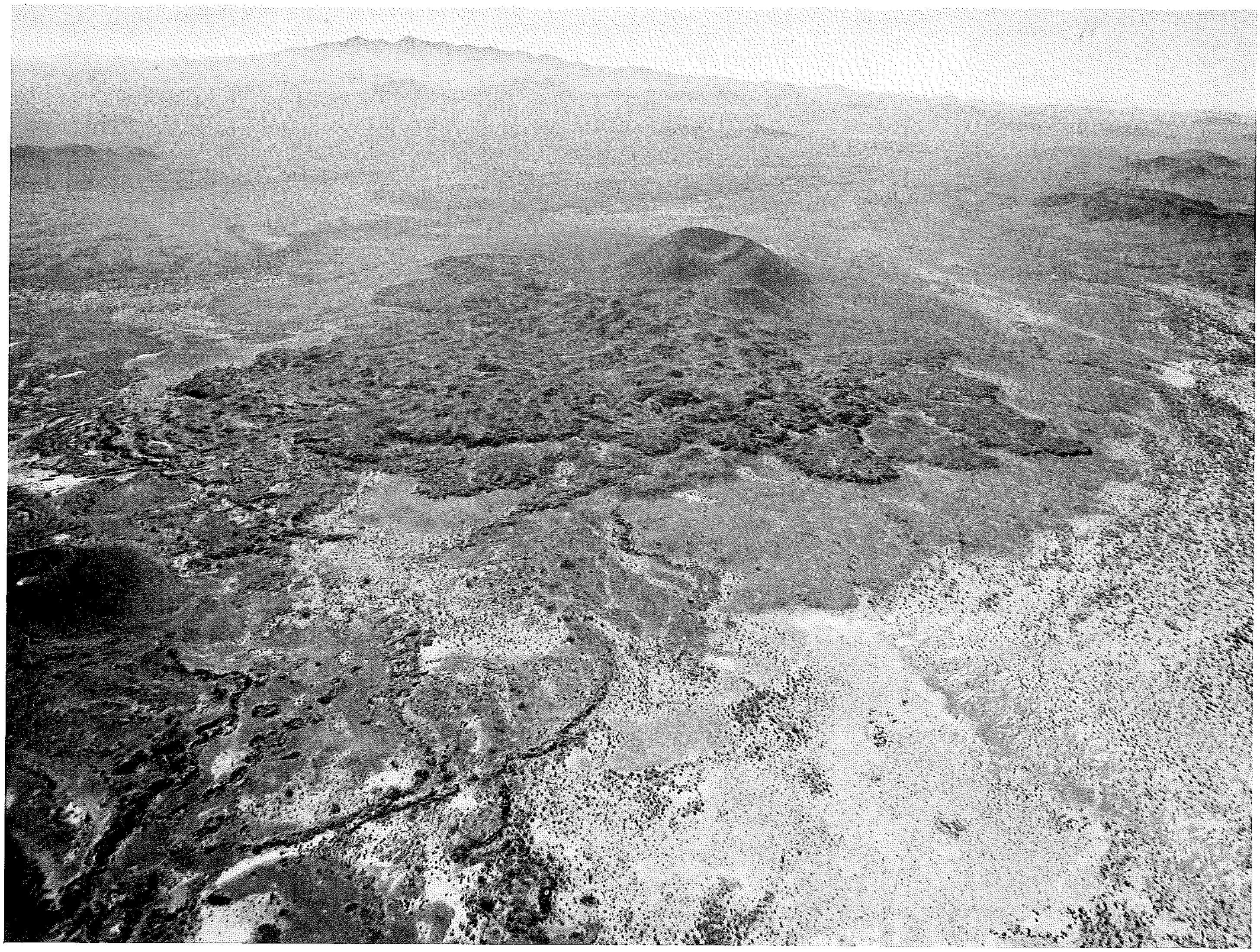


Figure 5. Large and small volcanoes of southern Arizona and northern Sonora. This unnamed monogenetic volcano in the Pinacate is a typical pyroclastic cone with its thin, small-area lava flows. The cone wall failed, probably from the pressure of a rising lava lake inside, and the lava poured out onto the desert. Volcan Santa Clara, the shield-shaped, composite volcanic mountain of Pinacate can be seen in the background, about 20 km to the south.

Volcanic bombs are blobs which have cooled sufficiently in flight to retain their coherence and shape on impact and do not weld to their neighbors. Blobs hot enough to weld together form "agglutinate," a relatively solid but porous mass. Occasional, more violent bursts of gas bubbles produce "clouds" of blobs which do not cool in flight; the still-liquid blobs coalesce on the cone slopes to form "rootless" lava flows (not directly connected to the vent) which move downslope.

Most cones are not constructed entirely of one type of pyroclastic material, but instead have layers of differing consistency. Agglutinate layers and rootless flows are more resistant to erosion than is cinder. One common shape for an eroding cone has a cliff at the top (Figure 4) where unwelded cinder has been stripped away from the outer slope and the agglutinate (closer to the vent) on the inner slope, stands as a vertical wall.

LAVA FLOWS AND LAVA CONES

The basaltic lava flows that accompany pyroclastic cones are usually less than 3 meters thick, owing to the low magma viscosity. They rarely extend more than a few kilometers from the cone (Figure 5), although some extend tens of kilometers from the cone in places where the lava flows within stream channels and is protected from heat loss. The vent mouth is an efficient separator of gas from liquid, so that both flowing lava and pyroclasts can be produced at the same time. The lava may flow beneath the cinder wall and appear to issue from the base of the cone or it may initially pool inside the crater and rise until the pressure causes the cone wall to break. A cone thus "breached" during its construction will remain open on that side. The north flow from Tecolote Cone in Pinacate rafted large portions of the western cone wall nearly 4 kilometers away from the cone (Figure 6). Most of Arizona's monogenetic cones are open on one side.

The surface of a new flow may be smooth, ropy "pahoehoe" or rough, clinkery "aa". Almost anyone who has studied geology is aware of these two "types" of lava but may not understand that the difference is minimal. Only one lava compositional type is involved—basalt—and these surface features are easily removed by weathering. Sharp spines and edges are eroded, dust and detritus fill the

Figure 6. Tecolote Cone, perhaps the youngest in Pinacate, was breached by lava outflow on its western (right) side. The flow in the foreground is littered with fragments of the wall and piles of cinder deposited atop it as it flowed outward, carrying them away like a conveyor belt.

surface pits, and eventually the surface (whether it was originally pahoehoe or aa) is reduced to "round rocks". This process commonly takes less than a half-million years and flow surfaces of that age are indistinguishable from those 20 million years older.

In some rare instances, basalt magma which lacks a significant volatile content will erupt without producing much pyroclastic material at any time during the eruption. Lava wells out of the conduit onto the ground and builds a broad, low-aspect lava cone (Figure 7) having a diameter-to-height ratio of 40 or 50 to 1. Lava cones are most common in the Sentinel Plain volcanic field west of Gila Bend.

MAAR CRATERS

Normal basalt magma which would otherwise produce a common strombolian-style eruption can, under unusual circumstances, generate substantial steam explosions if the

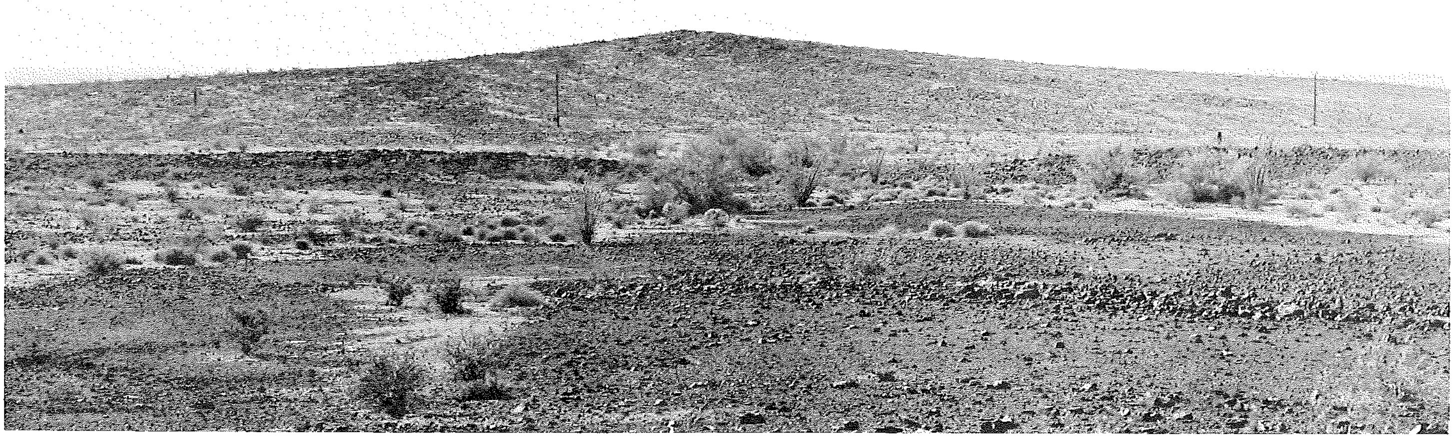


Figure 7. A low-aspect lava cone in the Sentinel Plain volcanic field. This field has 15 such cones which have very little pyroclastic material on them. They were created by effusion of relatively gas-free magma from the conduit.

magma is able to mix with and exchange its heat into water on the surface or at a shallow depth in the ground. These "hydromagmatic" or "hydrovolcanic" explosions are small by comparison with Plinian explosions of high viscosity magma, but they are much more powerful than the average strombolian eruption.

Hydrovolcanic eruptions create "maar" craters and tuff rings, the most distinctive and spectacular landforms to be found among monogenetic volcanoes (Figure 8). A maar is a destructional feature blasted into the pre-eruption land surface by numerous, repeated explosions. Although it is a type of caldera in a strict sense, a maar is *not* created by roof collapse into a shallow, rapidly evacuated magma chamber. A tuff ring or tuff cone (like Cerro Colorado-Figure 9) is constructed around the maar from debris falling out of the eruption cloud. This cloud is a "fluid system" of steam, water, chilled basalt glass, and fragments of country rock from the eruption site. The cloud deposits the solid material in characteristic high-energy bed forms (Figure 10) around the maar as it spreads radially outward in what is commonly called "base surge".

Figure 8. Three maar craters of northwest Pinacate. MacDougal is most distant (15 km), Molina is at lower left and Sykes is in the foreground (1 km in diameter). The two triangular dark patches above the solid lava in the far wall of Sykes are the remains of a cinder cone constructed during effusion of the fresh-appearing lava flows seen beneath the soft tuff on the left and extending into the far distance on the right. The steam eruption which excavated this crater and made the tuff ring was a later phase of the same strombolian eruption that made the destroyed cinder cone. This crater is one of the best examples of the interchangeability of strombolian and hydrovolcanic (steam-blast) eruption styles.

Of the volcanic fields shown on the map (Figure 1), only Sentinel Plain and those north of the Colorado River lack hydrovolcanic features. Pinacate has nine such features, including the most spectacular maar craters on the continent (Figure 8). The Hopi Buttes field was erupted into Pliocene-age Hopi Lake, resulting in surface landforms that are maar craters and tuff rings. Subsequent erosion has reduced much of this field to a series of volcanic necks (i.e., lava solidified in the conduits) and many of the constructional landforms are gone.

VOLCANOES AND CRUSTAL STRUCTURE

Crustal stresses and crustal structures affect the upward passage of basalt magma, not its generation. Whereas volcanic field locations do not seem to be controlled by crustal structures, a few fields, like Uinkaret, have vents lined up nearly parallel to the surface traces of normal (i.e., gravity) faults in the area. Magma can rise to the surface only when pressure within the magma chamber exceeds the weakest stress in the rocks surrounding it. Dikes intrude perpendicular to this "minimum horizontal compression" direction and normal fault traces are also perpendicular to this direction. For this reason, both normal faults and feeder dikes for volcanoes may be parallel on the surface. This has led to the erroneous conclusion that the faulting is somehow responsible for the volcanism. Basalt volcanism and normal faulting may both be the result of processes active in the mantle, but magma generation takes place at a far greater depth than faults can penetrate.

Figure 9. Cerro Colorado Tuff Cone in northeastern Pinacate. This cone is composed of hydrovolcanic tuff created by the interaction of basalt magma with ground water. Its interior is actually a shallow maar, which is not as spectacular as the others because it has no massive basalt flows to hold up its walls. The apron around the tuff cone is about 3 km across; Diaz Playa is beyond to the northwest. Photo: P. Kresan.

VOLCANOES AS HAZARDS

Volcanism in three of the area's volcanic fields is dormant, capable of awakening sometime in the future. The most recent, dated eruption took place at Sunset Crater in the San Francisco Mountain volcanic field in 1065 AD (Carbon-14 and tree ring date). Lavas appearing almost as fresh as Sunset's Bonito flow are found in Pinacate and Uinkaret and are probably no more than a few thousand years old. The rest of Arizona's volcanic fields lack young-appearing features and are possibly extinct, their magma systems cold. The youngest flows of the composite volcanic mountains are so old that the big volcanoes are also probably extinct.

Dormancy is the most common condition in Arizona's monogenetic volcanic fields. Their typical strombolian eruptions were of short duration, less than a year, whereas the recurrence interval was on the order of thousands to tens of thousands of years. The next volcanic eruption in Arizona will most probably be strombolian like the last one. As such, it will be nowhere near as hazardous as the big Mt. St. Helens eruption of 1980. It will most probably occur either in the Pinacate, San Francisco Mountain or Uinkaret volcanic field and, unless it is in or near Flagstaff (an unlikely possibility) it will cause little damage or disruption.

Dr. Daniel J. Lynch is a research scientist in the Laboratory of Isotope Geochemistry at the University of Arizona. A confirmed "volcano freak" since the age of five, he has worked on the San Bernardino volcanic field in Cochise County and on the Pinacate volcanic field of Sonora and Yuma County. Dan relishes the possibility of an eruption in one of Arizona's dormant volcanic fields but he is not optimistic.

ADDITIONAL READING

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