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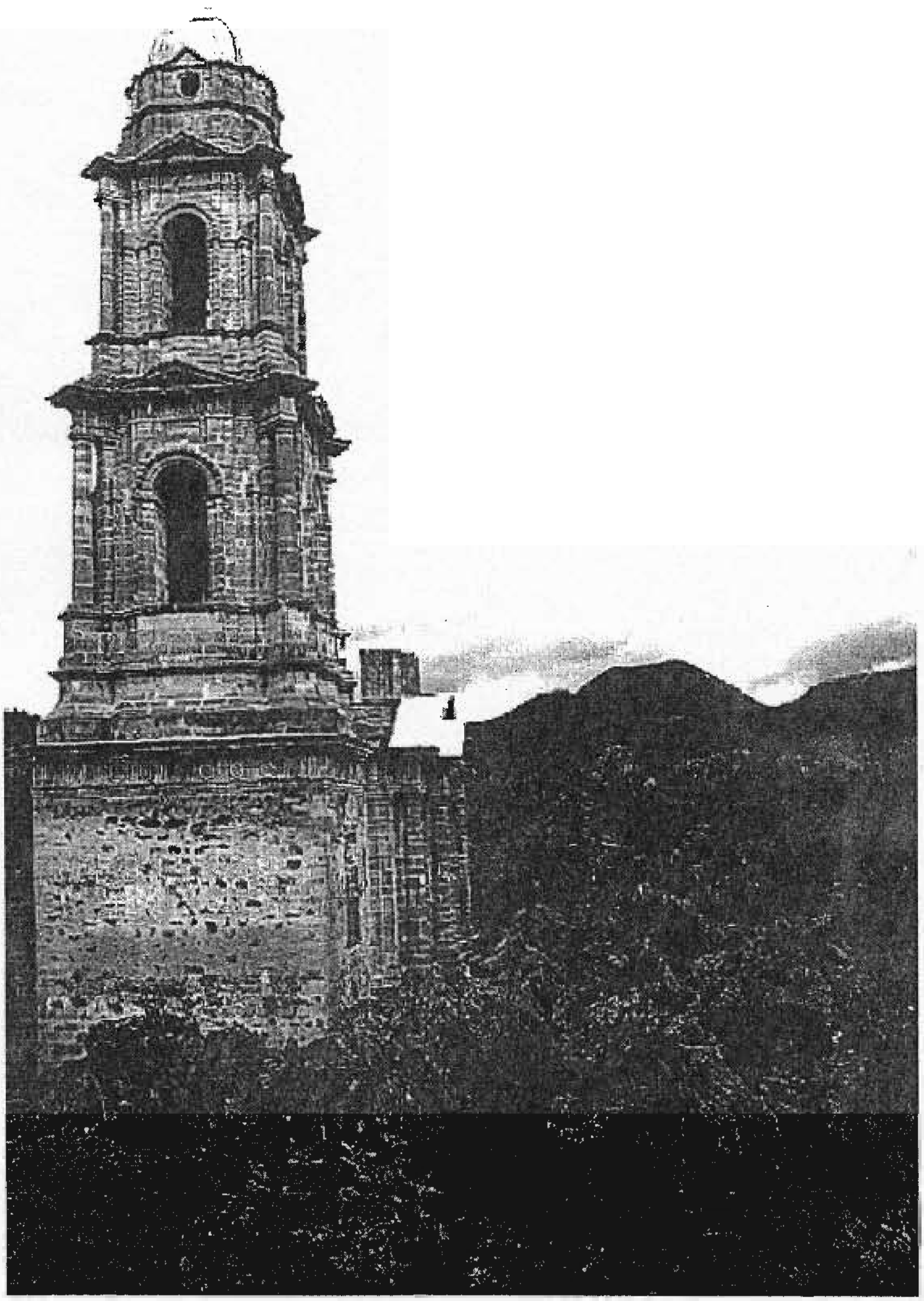
Excursion Number 9, January 22, 1997

Aerial Examination of Volcanoes Along the Front of the Western Trans-Mexican Volcanic Belt and a Visit to Parícutin



Fronticepiece. San Juan Parangaricutiro church, surrounded by lava in 1944, with Parícutin Volcano in the background to the S. The Nuevo Juatita vent mound is visible on Parícutin's left (NE) shoulder.

1997 IAVCEI GENERAL ASSEMBLY

EXCURSION NUMBER 9 (1 DAY): January 22, 1997

AERIAL EXAMINATION OF VOLCANOES ALONG THE FRONT OF THE WESTERN TRANS-MEXICAN VOLCANIC BELT AND A VISIT TO PARÍCUTIN

Leaders: *James F. Luhr and Hugo Delgado-Granados*

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INTRODUCTION

The goal of this fieldtrip is to obtain a birds-eye view of some of the major eruptive centers and structures near the volcanic front of the western Trans-Mexican Volcanic Belt, with abundant opportunities for aerial photography. The air route will take us from Puerto Vallarta 350 km ESE to Uruapan, where we will land for a hiking visit to Parícutin Volcano. In the late afternoon we will reboard the plane for the return flight to Puerto Vallarta. The area of interest is shown in Fig. 1, extending eastward from the Pacific coasts of Nayarit and Jalisco states to the eastern boundary of the Michoacán-Guanajuato Volcanic Field (~100.5°W).

Flight Plan

The approximate flight path for this field trip is shown on Fig. 1. This section gives an overview of major features we will see on the excursion.

After leaving Puerto Vallarta, we will fly over the Jalisco Block and two of its Plio-Quaternary volcanic fields: Mascota and Los Volcanes. Continuing eastward

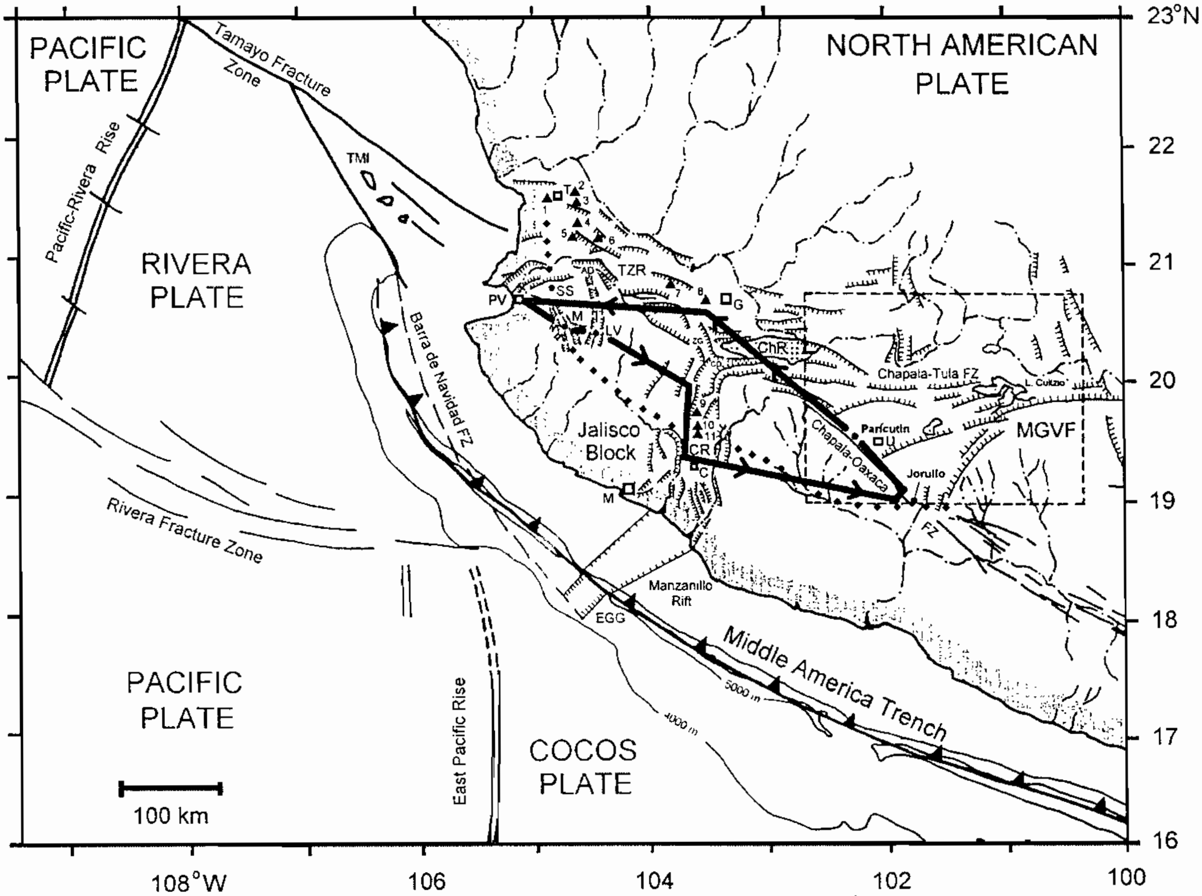


Fig. 1. Simplified map of the western Trans-Mexican Volcanic Belt and offshore tectonic features. The heavy black line shows the approximate flight path. The chain of diamonds shows the position of the volcanic front in this area. On-land faults were mostly taken from Johnson & Harrison (1990), with some modifications from Allan et al. (1991) and Carmichael et al. (1996). The three major rift zones of the westernmost Trans-Mexican Volcanic Belt are shown: CR, Colima Rift; ChR, Chapala Rift; TZR, Tepic-Zacoalco Rift. The SE end of the Tepic-Zacoalco Rift is called the Zacoalco Graben. Major volcanic centers associated with these rift zones are shown by triangles: 1, Volcán San Juan; 2, Volcán Las Navajas; 3, Volcán Sangangüey; 4, Volcán Tepetiltic; 5, Volcán San Pedro; 6, Volcán Ceboruco; 7, Volcán Tequila; 8, Sierra La Primavera; 9, Volcán Cántaro; 10, Nevado de Colima; 11, Volcán Colima. Within the Jalisco Block are shown three grabens and associated volcanic fields (dots): the Atenquillo Graben, containing the Los Volcanes Volcanic Field (LV), and the Mascota and Talpa Grabens, containing the Mascota Volcanic Field (M). The San Sebastian Volcanic Field (SS) lies north of the latter two grabens. Cutting across the Michoacán-Guanajuato Volcanic Field (dashed rectangle labeled MGVF) are the Chapala-Tula Fault Zone and the Chapala-Oaxaca Fault Zone (Johnson & Harrison, 1990). Dots show the historically active cinder cones Parícutin (P) and Jorullo (J). Open squares show major cities: T, Tepic; G, Guadalajara; PV, Puerto Vallarta; M, Manzanillo; C, Colima; U, Uruapan. Dash-dot lines show major rivers. Offshore features were mainly taken from Fisher (1961), DeMets & Stein (1990), and Bourgois & Michaud (1991).

will bring us to the Colima Rift Zone, which marks the eastern boundary of the Jalisco Block. We will observe the impressive structure of the Northern Colima Graben, the chain of three calc-alkaline volcanoes that occupy the floor of the Central Colima Rift to the south (Cántaro, Nevado de Colima, and Volcán Colima), and the alkaline cinder cones on the flanks of that chain. Continuing ESE we will skirt the southern edge of the Michoacán-Guanajuato Volcanic Field and then circle the cones and lava field of Jorullo Volcano, formed in 1759-1774. We will then travel to the NW and circle Parícutin Volcano and its lava field, formed in 1943-1952, before landing at Uruapan. There we will board vans for our hiking trip to Parícutin. On the return trip from Uruapan to Puerto Vallarta, we will head to the N and W with views of the Chapala Rift Zone and Lake Chapala, the city of Guadalajara, the late-Pleistocene Sierra la Primavera rhyolitic complex, and Volcán Tequila in the setting sun.

JALISCO BLOCK

Three large rift zones intersect in western Mexico, about 60 km SSW of Guadalajara, to form a structural triple junction (Fig. 1): the Tepic-Zacoalco Rift, the Colima Rift, and the Chapala Rift (Luhr et al., 1985; Allan et al., 1991). Two large fault systems also extend to the E and SE from the Chapala Rift across the Michoacán-Guanajuato Volcanic Field: the Chapala-Tula Fault Zone and the Chapala-Oaxaca Fault Zone (Johnson and Harrison, 1990). Other extensional structures occur to the SW, in the western part of the Jalisco Block, which is the name given to the SW corner of Mexico bounded by the Tepic-Zacoalco Rift to the N and the Colima Rift to the E (Allan et al., 1991).

Geologically, the Jalisco Block is the least known part of the western Trans-Mexican Volcanic Belt. Granodioritic batholiths with emplacement ages of 85-106 Ma are prominent in its western part, including those near Puerto Vallarta (Köhler et al., 1988; Zimmermann et al., 1988; Righter et al., 1995). Roughly coeval rhyolitic ash-flow tuffs (70-114 Ma) cover large parts of the Jalisco Block (Gastil et al., 1979a, 1979b; Wallace & Carmichael, 1989). These are distinctly older than ash-flow tuffs found N of the Tepic-Zacoalco Rift, and this fact has been used to define the N boundary of the Jalisco Block (Ferrari, 1995; Righter et al., 1995). The Jalisco Block stands high relative to the terrane N of the Tepic-Zacoalco Rift, apparently the result of Neogene uplift (Ferrari, 1995; Righter et al., 1995).

Few late-Cenozoic structures have been mapped in the Jalisco Block. Johnson & Harrison (1990) identified several graben structures in the same area that Wallace & Carmichael (1989; 1992) and Carmichael et al. (1996) later named the Talpa, Mascota, and Atenguillo Grabens (Figs. 1 and 2). These grabens are 2-5 km wide with up to 900 m of relief. Topography is subdued, and few young fault scarps have been identified. These structures are well defined, however, by N to WNW courses of tributaries to the Ameca River (Figs. 1 and 2).

Four discrete volcanic fields have been defined in the Jalisco Block (Fig. 2): Mascota, Los Volcanes, Atenguillo Graben, and San Sebastian. In each field, two distinct magma series erupted from neighboring cones during the same time interval: calc-alkaline (with *hy* or *q* in the CIPW norm) and lamprophyric (*ne* and in rare cases *lc* in the CIPW norm). The volcanic front in the western Trans-Mexican Volcanic Belt is now considered to extend from Volcán San Juan, through these four Jalisco Block volcanic fields, and then to Volcán Colima (Lange & Carmichael, 1990; 1991; Wallace & Carmichael, 1992) (chain of diamonds on Fig. 1). Both the calc-alkaline and alkaline suites formed from remarkably water-rich magmas. Hornblende is common in all volcanic-front suites, from Volcán San Juan, through the Jalisco Block fields, to the Colima Volcanic Complex. In the alkaline suites, water stabilized either hornblende or phlogopite and suppressed the crystallization of feldspars to the groundmass, giving many of these rocks the classic textures of lamprophyres ("glistening porphyries"). Lamprophyre terminology has been used in naming many of these rocks; the textural criteria are presence of hydrous phenocrysts and lack of feldspar phenocrysts (>0.3 mm). Minette is the most common lamprophyre found in the Jalisco Block fields.

Plate-Tectonic Significance

Luhr et al. (1985) and Allan et al. (1991) proposed that the structural triple junction that borders the Jalisco Block reflects initiation of a major continental rifting event, that will ultimately lead to transfer of the Rivera plate and the Jalisco Block (currently part of the North American plate) to the Pacific plate. This hypothesis was argued to be related to jumping of the Pacific-Rivera spreading ridge to the site of the Colima Rift (Fig. 1). Four similar eastward ridge jumps have progressed northward in sequence along the East Pacific Rise during the last 12 Ma (Van Andel et al., 1975; Klitgord & Mammerickx 1982; Mammerickx & Klitgord 1982), and the proposed on-going ridge jump would be a continuation of this series and the first event to intersect continental crust.

Several alternatives have been proposed to this model. Michaud et al. (1990) and Bourgois & Michaud (1991) argued that a similar transfer of the Jalisco Block to the Pacific plate is occurring, but placed the southern boundary of the transfer zone along the Barra de Navidad Fault and Tamayo Fracture Zone, rather than along the Rivera Fracture Zone (Fig. 1). This interpretation, however, runs counter to the history of northward-propagating ridge jumps along the East Pacific Rise, and

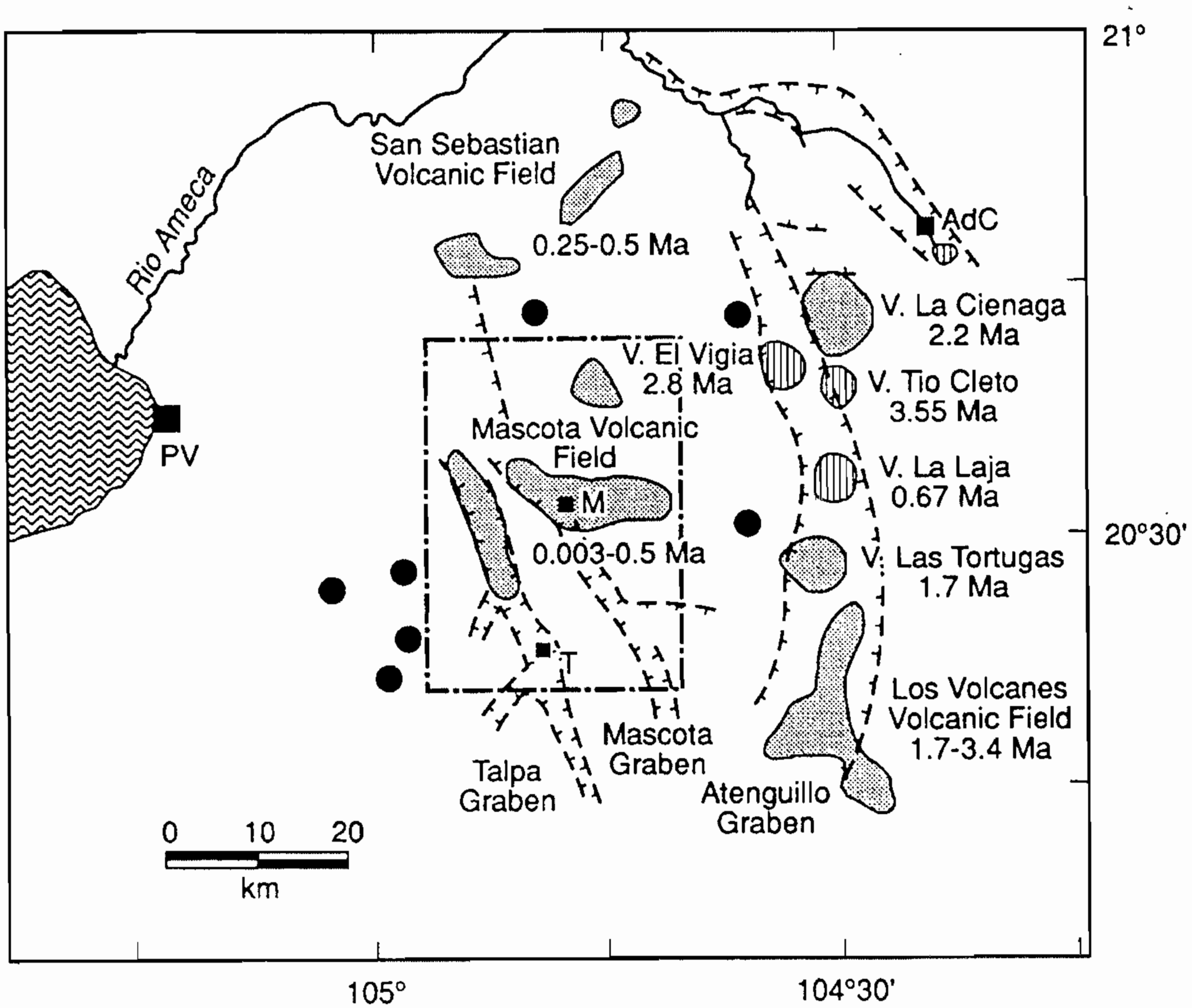


Fig. 2. The grabens and volcanic fields of the Jalisco Block. Dashed lines with ticks indicate faults and down-thrown directions for the main graben structures. Calc-alkaline and lamprophyric volcanic fields are stippled, and fields where intraplate-type basalts erupted are ruled. Peaks above 2500 m are shown by dots. M is Mascota, T is Talpa de Allende, PV is Puerto Vallarta, and AdC is Amatlan de Cañas. The dash-dot rectangle marks the area of the Mascota Volcanic Field shown in Fig. 3. Reproduced from Carmichael et al. (1996).

would result in a rather improbable configuration of ridge segments, with the current Pacific-Rivera Rise stranded well west of ridge segments to its north and south.

DeMets & Stein (1990) noted that oblique subduction of the Cocos plate leads to southeastward transport of crustal slivers along the southern Mexican coast. They envisioned the Colima Rift forming as a pull-apart basin at the trailing edge of this process. Their analysis of spreading rates along the Pacific-Rivera Rise indicated that spreading has increased over the last 3 Ma, and thus provided no support for waning activity at this ridge segment in advance of a shift of spreading to the site of the Colima Rift. Their model is well supported by field evidence for left-lateral translation of crustal blocks along the Mexican Volcanic Belt (Pasquaré et al., 1986; Suárez & Singh, 1986; Urrutia-Fucugauchi & Böhnel, 1988). This mechanism clearly appears to be operating within western Mexico, but alone cannot account for the extension in the Chapala Rift or active faulting along the Tepic-Zacoalco Rift.

Ferrari et al. (1994) and Ferrari & Elguera (1996) dismissed evidence presented in support of Quaternary right-lateral faulting along the Tepic-Zacoalco Rift by Nieto-Obregón et al. (1985), Allan (1986), Nieto-Obregón (1989), Allan et al. (1991), and Garduño & Tibaldi (1991), and proposed that no such motion has occurred since the Pliocene. Instead, they advocated trenchward motion of the Jalisco Block away from the North American plate in a form of intra-arc extension. Based on fault plane analysis and volcanic alignments, these authors argued that the Jalisco Block is moving southwest, rather than northwest as argued by Luhr et al. (1985) and Allan et al. (1991). This southwest motion might, however, reflect an initial dislodging of the Jalisco Block away from North America, prior to northwestward translation to follow Baja California as the next crustal block transferred to the Pacific plate.

A long-term Global Positioning System survey of western Mexico, conducted by a team of Mexican and U.S. scientists, was begun in March of 1995 (DeMets et al. 1995). Fifteen stations were established: eight within the Jalisco Block, one near the on-land triple junction, one within the Colima Rift, one north of the Tepic-Zacoalco Rift, and four east of the Colima Rift. Results of this study should eventually provide unequivocal evidence for the kinematic rates and directions of motion for the Jalisco Block and other crustal terranes in southwestern Mexico.

Various workers have emphasized that the on-going continental rifting event in western Mexico provides an excellent analog for the initial rifting of Baja California ~14 Ma (Luhr et al., 1985; Allan et al., 1991; Lyle & Ness, 1991). In the case of Baja's rifting, the slow continental stage lasted ~5-6 Ma and was probably followed by a rapid transition to sea-floor spreading (Lyle & Ness, 1991). The Colima Rift, whose floor is now at an average elevation of ~1 km, has apparently been extending for ~5 Ma, and by analogy with Baja rifting, may soon evolve to marine incursion and sea-floor spreading. Modeling of gravity data collected along the axis of the Colima Rift indicated a crustal thickness of 30-46 km, similar to results for the rift flanks (Urrutia-Fucugauchi & Molina-Garza, 1992). Likewise, heatflow is not anomalously high within the Colima Rift (Sedlock et al., 1993). Thus, the Colima Rift is at an early stage of continental rifting and has not evolved to the point of demonstrable crustal thinning and enhanced heatflow.

Mascota Volcanic Field

The NNW-trending Mascota and Talpa Grabens are 2-5 km wide and exhibit up to 900 m of relief on their walls, where they are cut into deeply dissected Cretaceous ash-flow tuffs, metasedimentary rocks, and granitic plutons (Carmichael et al., 1996). The grabens occur in rugged country with peaks above 2,500 m (Fig. 2). The valley floors are flat-bottomed with meandering, northward-flowing rivers, and support a flourishing agricultural economy.

As seen in Figs. 2 and 3, volcanism is essentially confined to the two grabens. Eruptive activity began ~0.5 Ma and continued into the latest Quaternary. It is dominated by lamprophyres (minettes, absarokites, spessartites, hornblende lamprophyres) and calc-alkaline basaltic andesites and andesites (Lange & Carmichael,

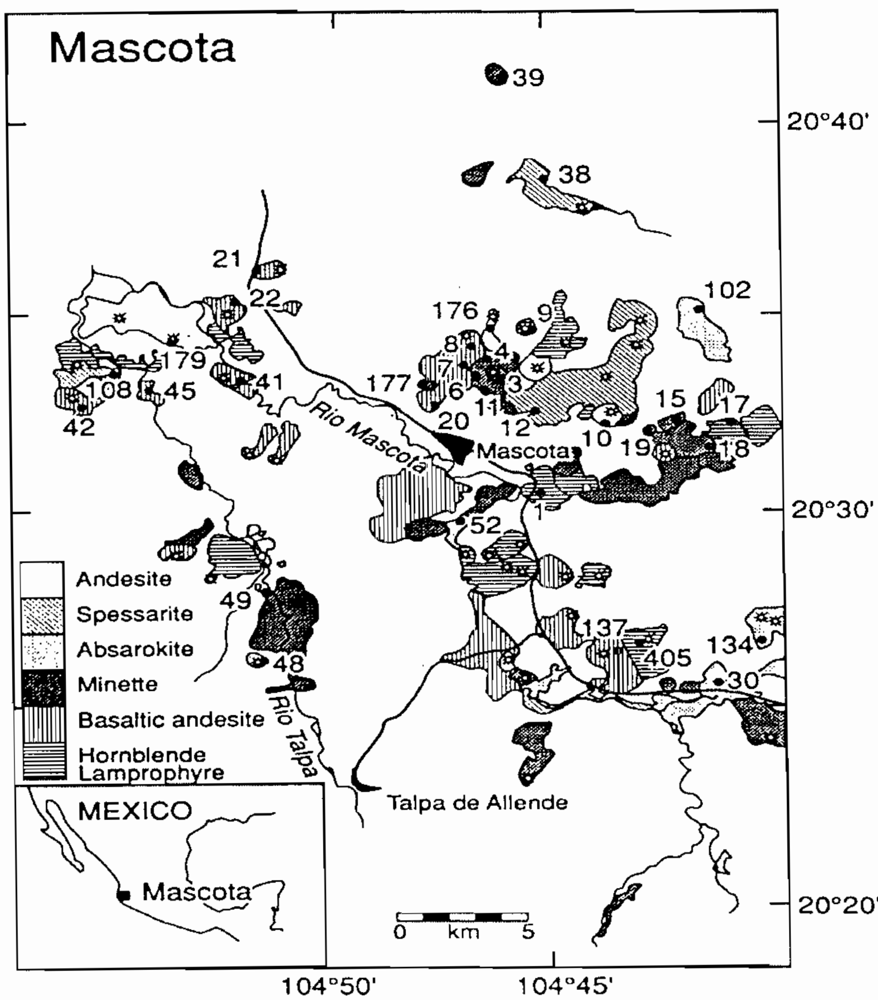


Fig. 3. Geological map of the younger volcanic rocks of the Mascota area. Locations of analyzed samples are represented by solid dots. Eruptive centers are shown by stars. Solid lines show main roads. Reproduced from Carmichael et al. (1996).

1990; Carmichael et al., 1996). These various rock types are almost randomly distributed throughout the field (Fig. 3). The Mascota minettes are the youngest known lamprophyres on Earth, with ages as low as 68,000 ± 80,000 years (Carmichael et al., 1996) and youthful cone morphologies (Fig. 4). About 50 km NNE from Mascota is the San Sebastian Field (Fig. 2), where lamprophyric (minette, absarokite, and kersantite) and calc-alkaline (basaltic andesite and hornblende andesite) magmas also issued from neighboring cinder cones during the interval 0.48-0.26 Ma (Lange & Carmichael, 1990; 1991).

Los Volcanes Volcanic Field

The Los Volcanes Field (Figs. 2, 5 and 6) lies at the S end of the Atenguillo Graben, which continues northward for 65 km. The volcanic field covers an estimated 285 km^2 and has a volume of about 30 km^3 (Wallace & Carmichael, 1992). The topography is quite subdued (Fig. 6). The most prominent volcanic landforms are small lava cones and flat-topped lava flows. Like Mascota, the Los Volcanes field also includes a wide variety of lamprophyric (minette, leucitite, vogesite, absarokite, trachybasalt, trachy-andesite) and calc-alkaline (basalt, basaltic andesite, andesite) rock types. Dated samples range from 3.4 to 1.7 Ma and show that the calc-alkaline and alkaline magmas were contemporaneous (Wallace & Carmichael, 1989; 1992).

Along the Atenguillo Graben to the north, Righter & Carmichael (1992) described several Plio-Pleistocene (3.6-0.6 Ma) shield volcanoes and lava plateaus built either of intraplate-type alkali basalt, hawaiite, and mugearite, or of calc-alkaline basaltic andesite (Fig. 2).

COLIMA RIFT

The Colima Rift extends southward for ~160 km from the rift intersection area to the Pacific Coast (Figs. 7 and 8). The northern Colima Rift is 20 km wide and displays a well formed graben structure with steep walls rising up to ~1,500 m above the graben floor and its playa lakes. Modeling of gravity data indicate the graben floor to be underlain by ~1,000 m of sediments (Allan 1986; Allan et al., 1991). The same authors estimated total

Fig. 4. Aerial photograph of the valley just NE of Mascota village, looking to the N. On the left is the a very rugged calc-alkaline basaltic andesite lava flow from Volcán Malpais, which is located at the upper end of the lava flow. In the center of the photo is minette cinder cone Volcán Molcajete, the second-youngest dated cone in the field: K-Ar age on phlogopite is 76 ± 10 ka. To its left is the smaller minette cinder cone Volcán Novillero (open to the E), dated by K-Ar on phlogopite at 282 ± 100 ka (dates from Carmichael et al., 1996). Photo by Steven A. Nelson.

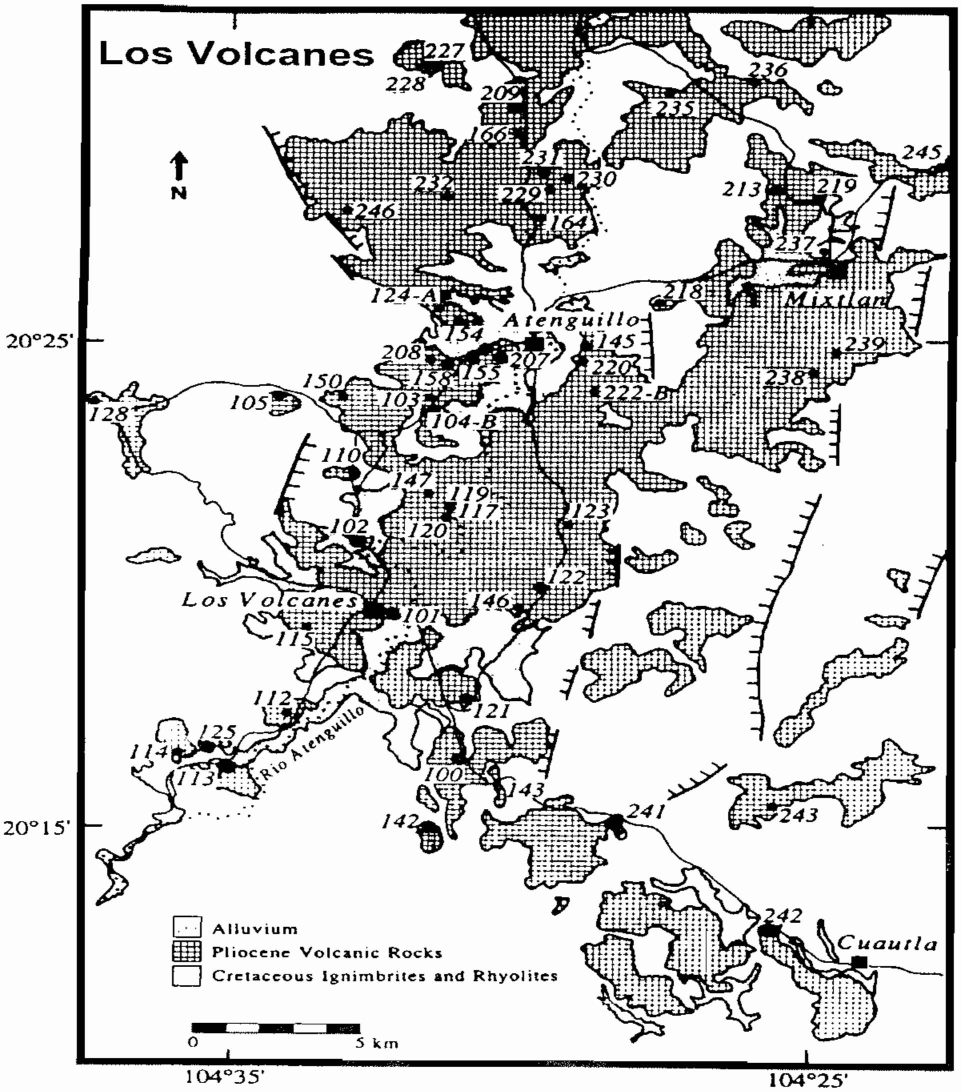


Fig. 5. Geological map of the Los Volcanes volcanic field showing the areal extent of late-Pliocene lavas. Locations of analyzed samples are represented by solid dots. Normal faults are shown as lines with hachures on the down-thrown side. Squares mark the positions of towns, solid lines indicate roads, and the dotted line shows Rio Atenguillo. Reproduced from Wallace & Carmichael (1992).

downdropping as 2.5 km, and E-W extension as 1.5-3.3 km (6-13%). As discussed below, the earliest dated lamprophyric volcanic rocks in the Colima Rift walls are ~4.7 Ma, and this has been suggested to represent the time of initial extension (Allan, 1986; Allan et al., 1991). The central Colima Rift (Fig. 8A) begins at the latitude of the Colima Volcanic Complex, where the Toliman graben (Herrera, 1967) merges from the NW to broaden the Colima Rift to a width of 50-60 km (Allan et al., 1991). The southern Colima Rift begins ~5 km S of Colima City, and the extensional style changes dramatically. The southern Colima Rift lacks an obvious graben structure, and based on field mapping and geophysical surveys, Serpa et al. (1992) have argued that N-S-trending landforms in the area formed by erosion of older structures and are not related to modern extension. Bandy et al. (1993), however, modeled gravity data in the southern Colima Rift as indicating two major NE-SW grabens with a total width of ~100 km and up to 8 km of sedimentary fill. Other evidence in support of active extension in the southern Colima Rift is its offshore continuation as the Manzanillo Rift (Fig. 1) (Bourgois et al., 1988; Michaud et al., 1990; Bourgois & Michaud, 1991). The Manzanillo Rift is a 60-km-wide depression with 1 km of vertical offset, containing a growing quartzo-feldspathic sedimentary fan and fault-controlled submarine canyons. The base of the sedimentary fan may mark the beginning of the Colima Rift and serve as an analog for growth of the Magdalena Fan (14.5-13 Ma) during the early stages of continental rifting associated with the separation of Baja California (Lyle & Ness, 1991)

As in the case for the Jalisco Block volcanic fields, two main magma series have erupted within the Colima Rift, calc-alkaline and lamprophyric. These two series can be found interbedded within the graben walls in the northern and central Colima Rift, where calc-alkaline rocks extend back to ~10 Ma and the lamprophyres extend to ~4.7 Ma (Allan and Carmichael, 1984; Allan et al., 1991). Both series continued to erupt during the Quaternary, as described below. Significantly, no lamprophyric rocks are found in the walls of the Zacoalco Graben, whose "domino" style of faulting contrasts with the classical opposed graben faults of the northern and central Colima Rift (Fig. 8B) (Allan et al., 1991).

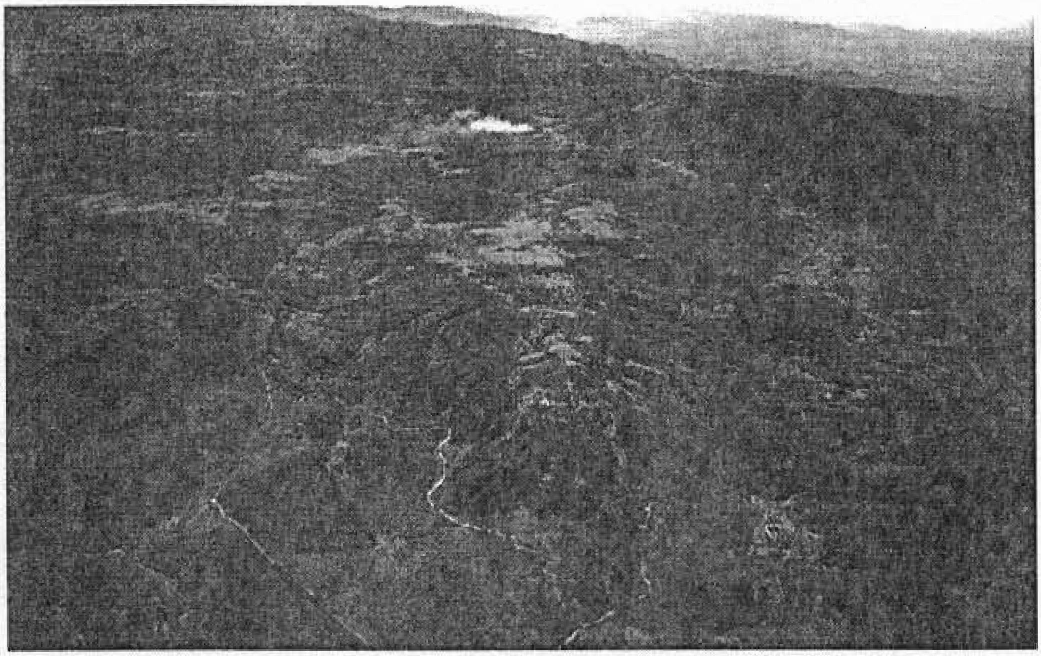


Fig. 6. Side-looking aerial photograph toward the south of the southern part of the Los Volcanes volcanic field, showing the subdued eroded topography of the Pliocene volcanic rocks and Cretaceous ignimbrites and rhyolites. Photo taken in 1942 by Defense Intelligence Agency: track 31L, image # 2-4008, 1-L121, 117.

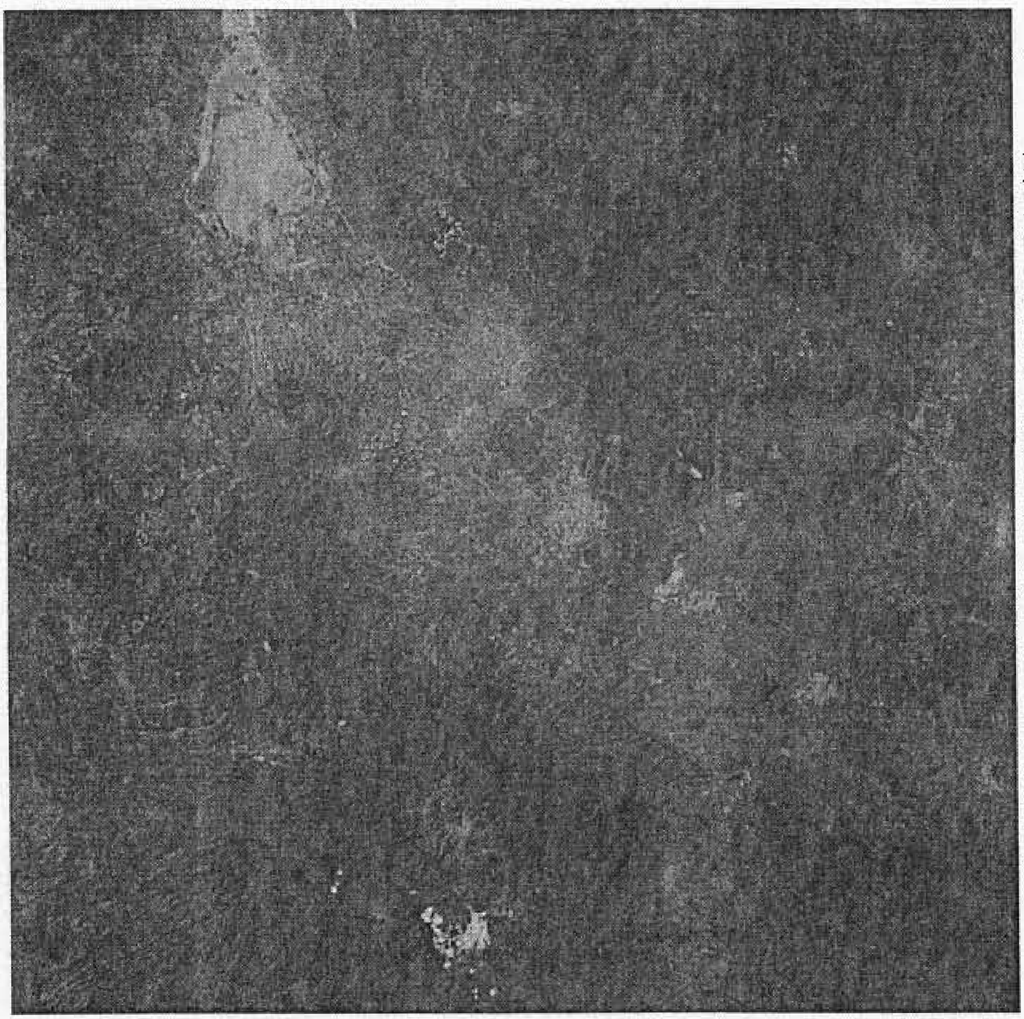


Fig. 7. View of the Northern and Central Colima Grabens from the Space Shuttle. North is to the upper left and the image width is about 65 km. In the lower part of the view the summit of Volcán Colima is partly obscured by clouds. Five and a half km to its N is the unobscured summit of Nevado de Colima. To its N, in turn, is the dark forested shape of Volcán Cántaro. East of Cántaro is the city of Ciudad Guzman. The light area in the upper left is the playa lakebed of Laguna Sayula, which occupies the Northern Colima Graben. Some of the graben fault scarps are visible. NASA image: 51-A-32-0049.

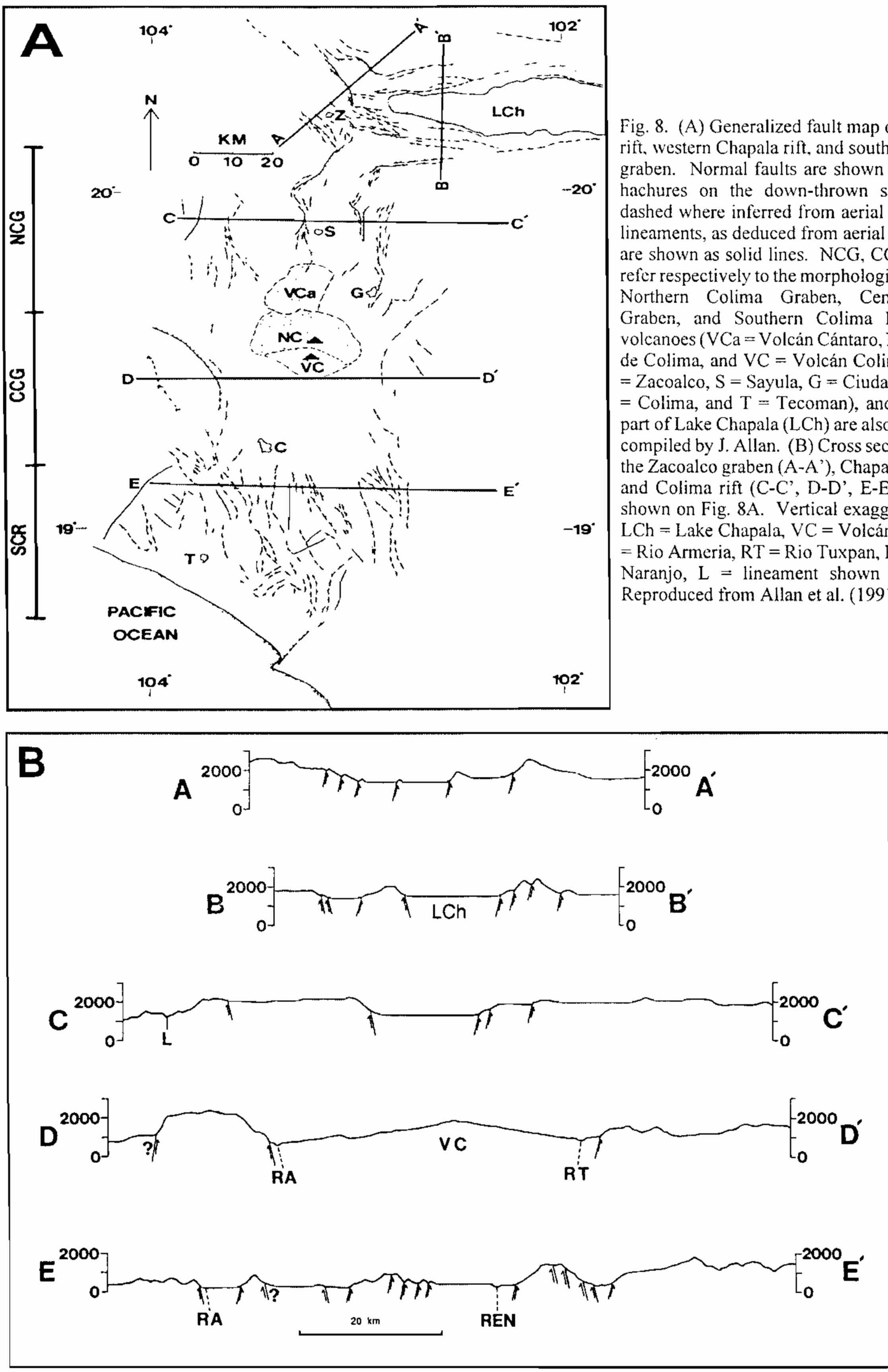


Fig. 8. (A) Generalized fault map of the Colima rift, western Chapala rift, and southern Zacoalco graben. Normal faults are shown as lines with hachures on the down-thrown side, and are dashed where inferred from aerial photographs; lineaments, as deduced from aerial photographs, are shown as solid lines. NCG, CCG, and SCR refer respectively to the morphological divisions: Northern Colima Graben, Central Colima Graben, and Southern Colima Rift. Large volcanoes (VCa = Volcán Cántaro, NC = Nevado de Colima, and VC = Volcán Colima), cities (Z = Zacoalco, S = Sayula, G = Ciudad Guzman, C = Colima, and T = Tecoman), and the western part of Lake Chapala (LCh) are also shown. Map compiled by J. Allan. (B) Cross sections through the Zacoalco graben (A-A'), Chapala rift (B-B'), and Colima rift (C-C', D-D', E-E'). Locations shown on Fig. 8A. Vertical exaggeration 2.5X. LCh = Lake Chapala, VC = Volcán Colima, RA = Rio Armeria, RT = Rio Tuxpan, REN = Rio El Naranjo, L = lineament shown on Fig. 8A. Reproduced from Allan et al. (1991).

Cántaro-Colima Volcanic Chain

Since the mid-Pleistocene, calc-alkaline eruptions have been mainly confined to the Colima Rift floor, where a southward-younging chain of three major calc-alkaline volcanoes has grown: Volcán Cántaro, Nevado de Colima, Volcán Colima (Figs. 9 and 10). Magma compositions have become progressively more primitive as vent position has migrated toward the trench.

Volcán Cántaro, in the north, is an eroded andesite-dacite cone that rises to 2,925 m from a base at about 1,600 m (Luhr and Carmichael, 1990b). Allan (1986) reported four K-Ar ages of 1.66-0.95 Ma for Çántaro lavas and domes.

Following formation of Volcán Cántaro, the focus of andesitic magmatism shifted southward by about 16 km and the massive cone of Nevado de Colima began to grow. Robin et al. (1984; 1987) discussed the geologic and petrologic evolution of the Colima Volcanic Complex, which includes both Nevado and the younger Volcán Colima. They divided the evolution of Nevado into 3 stages, separated by episodes of caldera formation. Stage I saw the growth of a large andesite-dacite cone, for which Robin et al. (1984) reported K-Ar ages of 0.53-0.35 Ma. The same authors reported ages of 0.29-0.14 Ma for andesitic lavas from the small stage-II cone, which collapsed to form a Mount St. Helens-type volcanic debris avalanche directed toward the east (Robin et al., 1990). Stoopes and Sheridan (1992) reported a ^{14}C age of 18,520 years from a carbonized tree trunk embedded in this debris-avalanche deposit. During stage III, an andesitic cone formed in the avalanche caldera. This summit cone is only slightly eroded and reaches an elevation of 4,320 m (Fig. 9).

The focus of activity shifted southward again by about 5½ km as the cone of Volcán Colima began to grow. The age of the first eruption from Volcán Colima is not known, but Robin et al. (1984; 1987) argued that it probably took place during Stage II activity at Nevado; thus, the active periods of the two volcanoes may have overlapped for a considerable time. One or more times during the last 10,000 years Volcán Colima has built itself to great height (probably 4,100 m) only to collapse

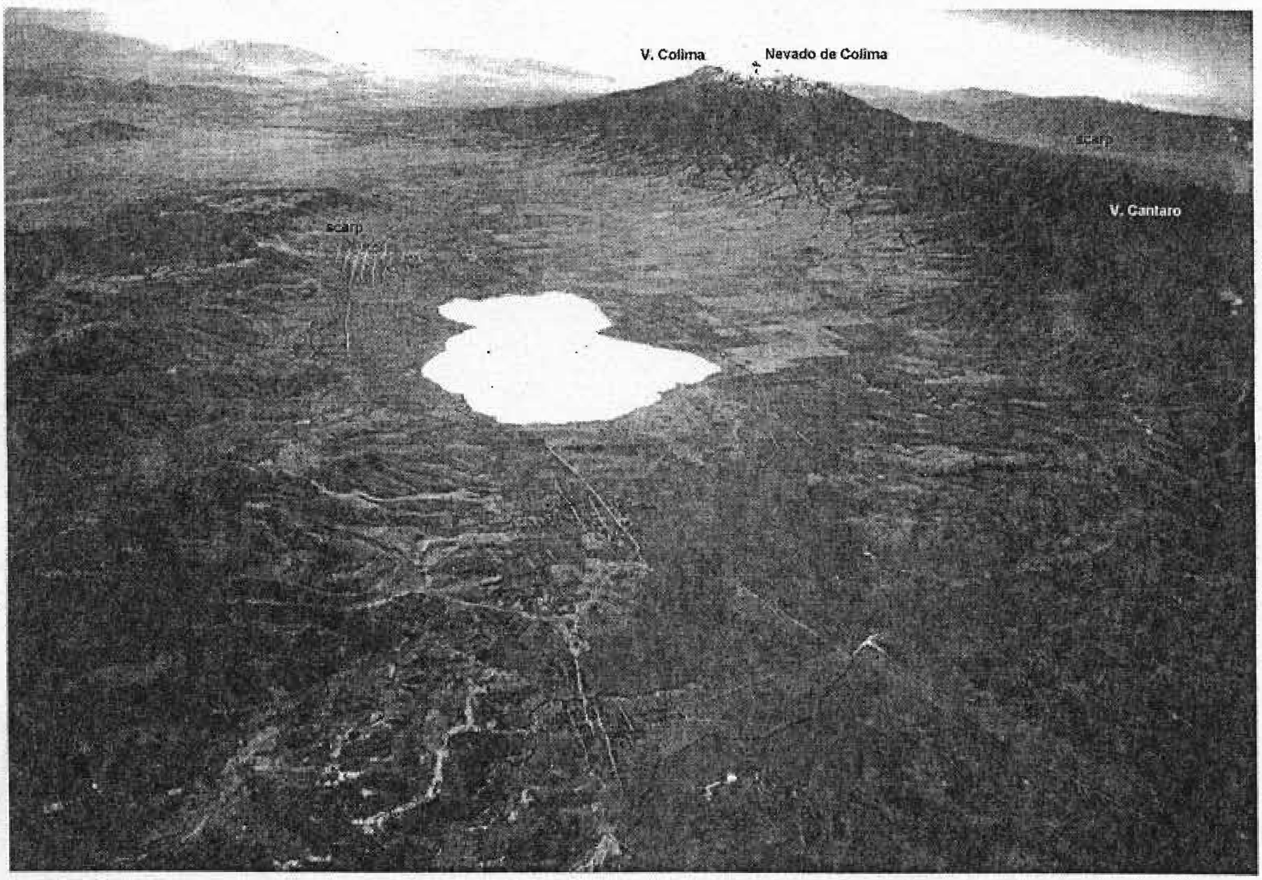


Fig. 9. Aerial view to the SW of the Northern and Central Colima Graben (see Fig. 8A). The southward-younging Cántaro-Nevado-Colima volcanic chain is clearly visible as are several graben fault scarps. The labeled scarp on the left is just S of Ciudad Guzman. The large white patch is Laguana Zapotitlan, which floods the rift floor E of Volcán Cántaro. For orientation, this view is from the upper right corner of the map shown in Fig. 10. Photo taken in 1942 by Defense Intelligence Agency: track 31L, image # 2-4008, 1-L73, 117.

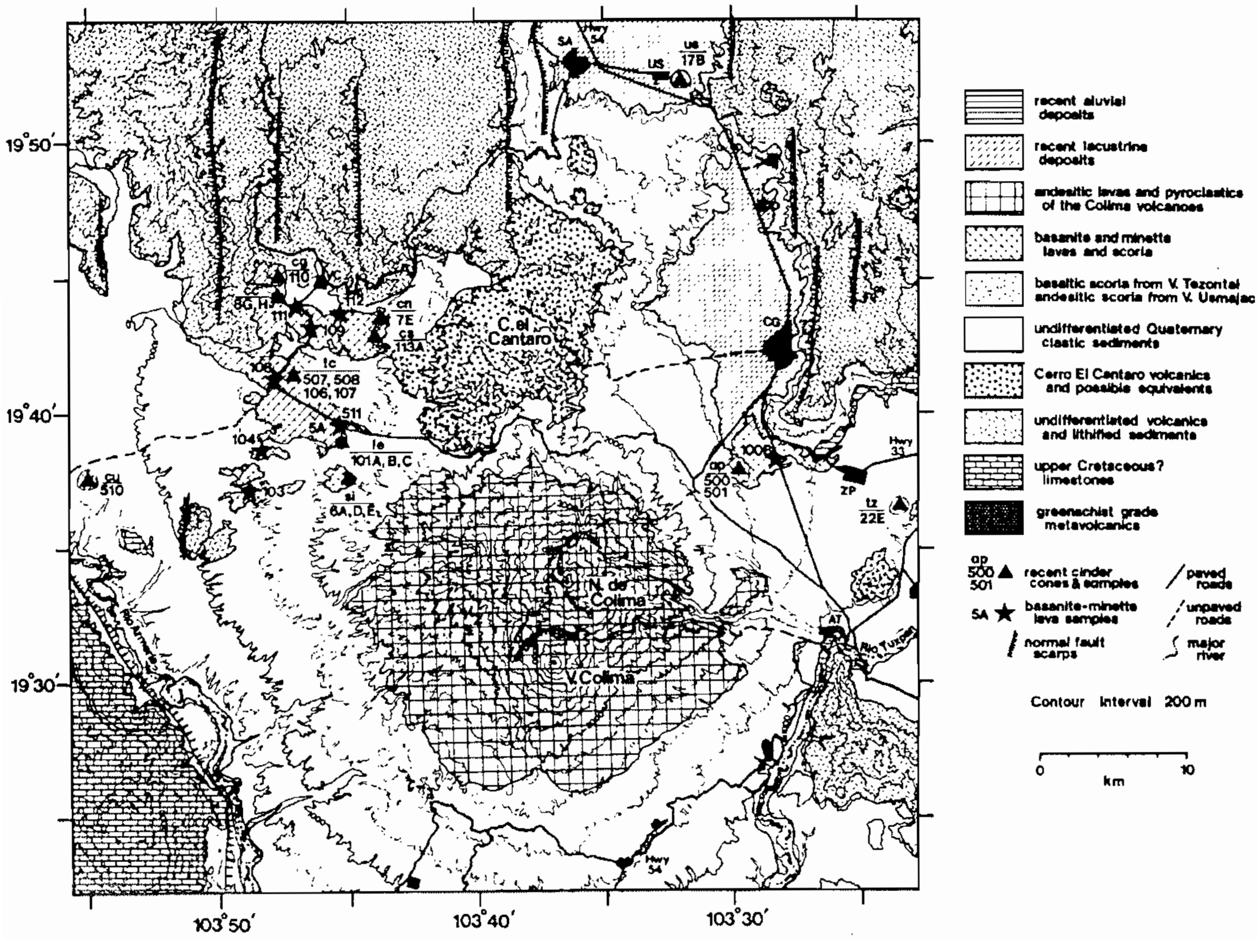


Fig. 10. Geological map of the central Colima Rift Zone. Abbreviated cities: AT, Atenquique; CG, Ciudad Guzman; SA, Sayula; US, Usmajac; VC, Venustiano Carranza; ZP, Zapotiltic. Abbreviated cinder cones: ap, Apaxtepec; tc, Telcampana; cc, Comal Chico; cg, Comal Grande; le, La Erita; cn, El Carpintero Norte; si, San Isidro; cs, El Carpintero Sur; tz, Tezontal; cu, Cuauhtemoc; us, Usmajac. Reproduced from Luhr & Carmichael (1981).

gravitationally into a large volcanic debris avalanche of the Mount St. Helens type (Luhr and Prestegaard, 1988; Robin et al., 1990; Stoopes and Sheridan, 1992). The last of these collapse events, perhaps just 3,000-4,000 years ago, left a horseshoe-shaped caldera, 5 km in diameter, and open to the SW (Figs. 10 and 11). Since that time, an andesitic composite cone has grown within the horseshoe-shaped summit caldera. This cone has now reached a height of over 4,000 m, and is one of the most active volcanoes in North America (Figs. 11 and 12). Volcán Colima has erupted frequently in historical times (Luhr, 1981; Medina-Martinez, 1983), including major explosive eruptions in 1818 and 1913, and important lava eruptions in 1869, 1961, 1975-76, 1981-82, and 1991. In both its lavas and tephra, Volcán Colima is dominated by medium-K, hornblende-andesite compositions, quite typical for continental subduction-zone volcanoes (Luhr and Carmichael, 1980; 1982; 1990a; 1990b; Luhr, 1993).

Flanking Cinder Cones

Like the calc-alkaline magmas that built the Cántaro-Colima volcanic chain, the contemporaneous lamprophyric magmas also became progressively more primitive as vent position migrated toward the trench. The most primitive of the Colima Rift lamprophyres erupted as cinder cones (Figs. 10 and 13) and associated lava flows on the flanks of the Cántaro-Colima volcanoes (Luhr and Carmichael, 1981; Luhr et al., 1989). Hooper (1995) used morphological analysis to estimate ages of 200,000 years to 20,000 years for these cinder cones. Lava and scoriae samples from the cinder cones form a complete gradation between basanites (with olivine ± plagioclase ± clinopyroxene phenocrysts) and minettes (with phlogopite phenocrysts in addition to these). The abundances of K, P, Ba, Sr, La, and other incompatible

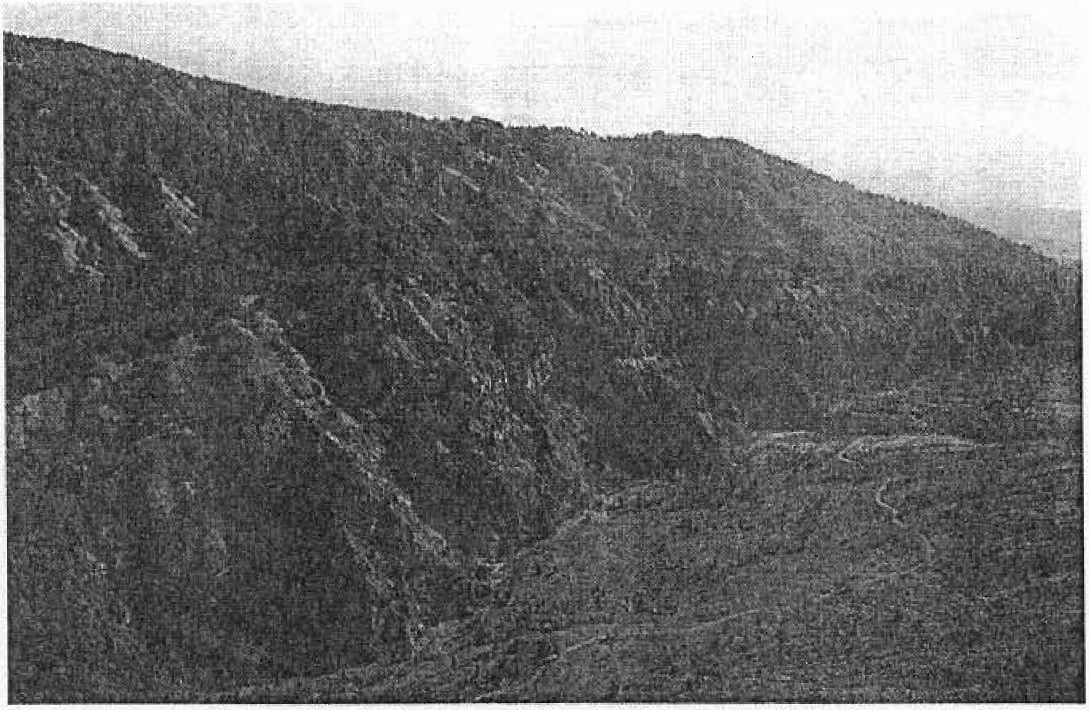


Fig. 11. Aerial view to NE of the caldera wall of Volcán Colima in 1981. The north flank of Nevado de Colima is visible to the left. Lava flows on at the NW foot of Colima's post-caldera cone are visible on the right, sloping down to the caldera wall. The caldera wall is up to 350 m high.

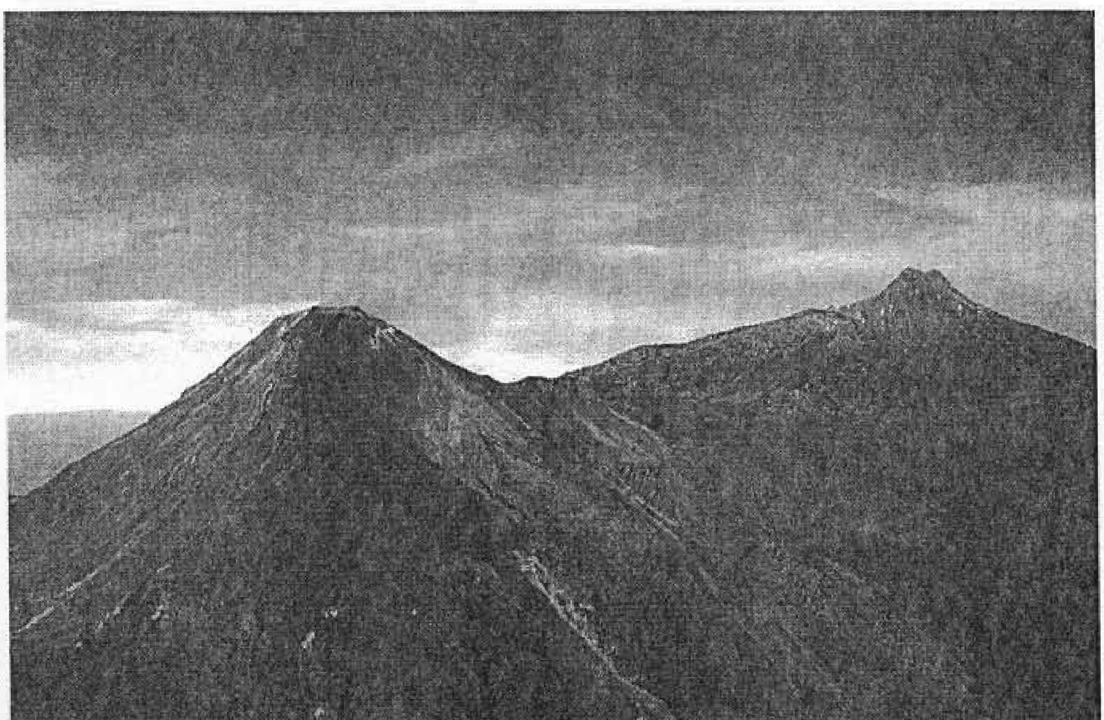


Fig. 12. Aerial view to the NNW of the Colima volcanoes in 1981. In the foreground is Volcán Colima. During the 1975-76 eruption, one lobe of dark block lava spilled over the SE rim, flowed partway down the upper cone, and then divided into two lobes. To the right of the main cone, where the profiles of the two large volcanoes meet, is the parasitic vent Volcancito, which in 1869 poured out the large mass of gray andesitic lavas that extends down and to the right from it. In the background is the Stage-III cone at the summit of Nevado de Colima cone, which at 4,320 m marks the highest point in the Cántaro-Colima volcanic chain. Photo by James F. Allan.

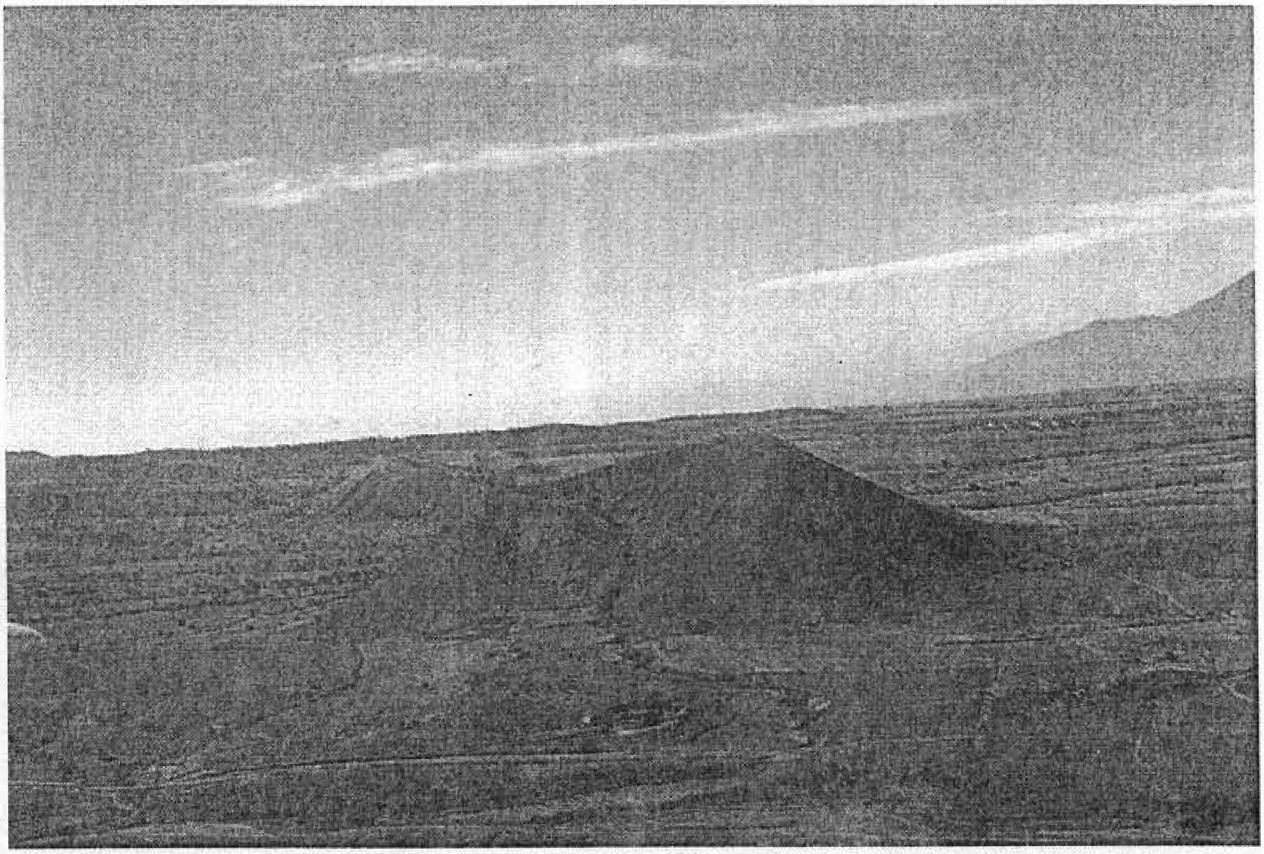


Fig. 13. View from the air looking south over two lamprophyric cinder cones on the west side of the calc-alkaline Cántaro-Colima volcanic chain in 1981. In the foreground is Volcán La Erita, which is open to the north. The circular pit to the north of La Erita is a cinder quarry. In the background, on a N-S alignment with La Erita, is Volcán San Isidro, which itself is elongated N-S. See Fig. 10 for orientation.

trace elements increase systematically with the amount of phlogopite (Luhr and Carmichael, 1981).

MICHOACÁN-GUANAJUATO VOLCANIC FIELD

From the southern end of the Colima Rift, we will turn E toward the Michoacán-Guanajuato Volcanic Field. This field measures 250 km from E to W, and 200 km from N to S, covering an area of 40,000 km^2. It is a unique part of the Trans-Mexican Volcanic Belt because it lacks the young large composite volcanoes dominant in other parts. Instead, it contains more than 1,000 small volcanic centers, including cinder cones, lava flows, maars, and lava cones, along with about 300 medium-sized volcanic centers, mostly shield volcanoes with diameters of about 10 km (Hasenaka and Carmichael, 1985a; 1985b; 1987; Ban et al., 1992). Only two of the cinder cones were formed during historical time: Jorullo in 1759-1774, and Parícutin in 1943-1952. We will circle both of these volcanoes and associated lava fields for aerial inspection and photography, and then travel to Parícutin by van for a hiking excursion.

A map showing the distribution of volcanoes in the Michoacán-Guanajuato Volcanic Field is given in Fig. 14A. Few volcanoes occur closer than 200 km to the Middle America Trench. The concentration of volcanoes is greatest about 250 km from the trench, and approximately 75% of the volcanoes are found between 200 km and 300 km. Farther than 300 km, the number of volcanoes decreases; the most distant cinder cone is 440 km from the trench. A local concentration of volcanoes at 380 km corresponds to the maar cluster of Valle de Santiago (Hasenaka and Carmichael (1985a). In general, the cinder cones are randomly spaced and indicate no preferred orientation. A small number of closely associated cinder cones, however, show local alignments; these trend E-W in the northern part of the volcanic field, ENE in the middle part, and NE in the southern part near the volcanic front (Fig. 14A: Hasenaka and Carmichael, 1985a). Connor (1990) evaluated clustering among the cones of the Michoacán-Guanajuato Volcanic Field. He concluded that 75% of the cinder cones belong to 8 clusters of 45-159 cones. The clusters were found to correlate with petrological groupings recognized by Hasenaka and Carmichael (1987). The overall cone density in the MGVF is 2.5 volcanoes/100 km^2 (1040 vents/40,000 km^2). The highest cone density of 11 volcanoes/100 km^2 is calculated for the Parícutin region (141 volcanoes/1250 km^2) (Hasenaka and Carmichael, 1985a).

Hasenaka and Carmichael (1985a) established the ages of 7 cinder cones through radiocarbon dating and found a systematic relationship between these ages and the extent of gullying on the cones slopes. They used these results to estimate ages for other young cinder cones, and concluded that the Michoacán-Guanajuato field contains 78 volcanoes that erupted during the last 40,000 years. All of them, including Jorullo and Parícutin, are situated in the S, and many belong to NE alignments of cones, parallel to the relative motion vector for the Cocos and North American Plates (Minster and Jordan, 1978) (Fig. 14B).

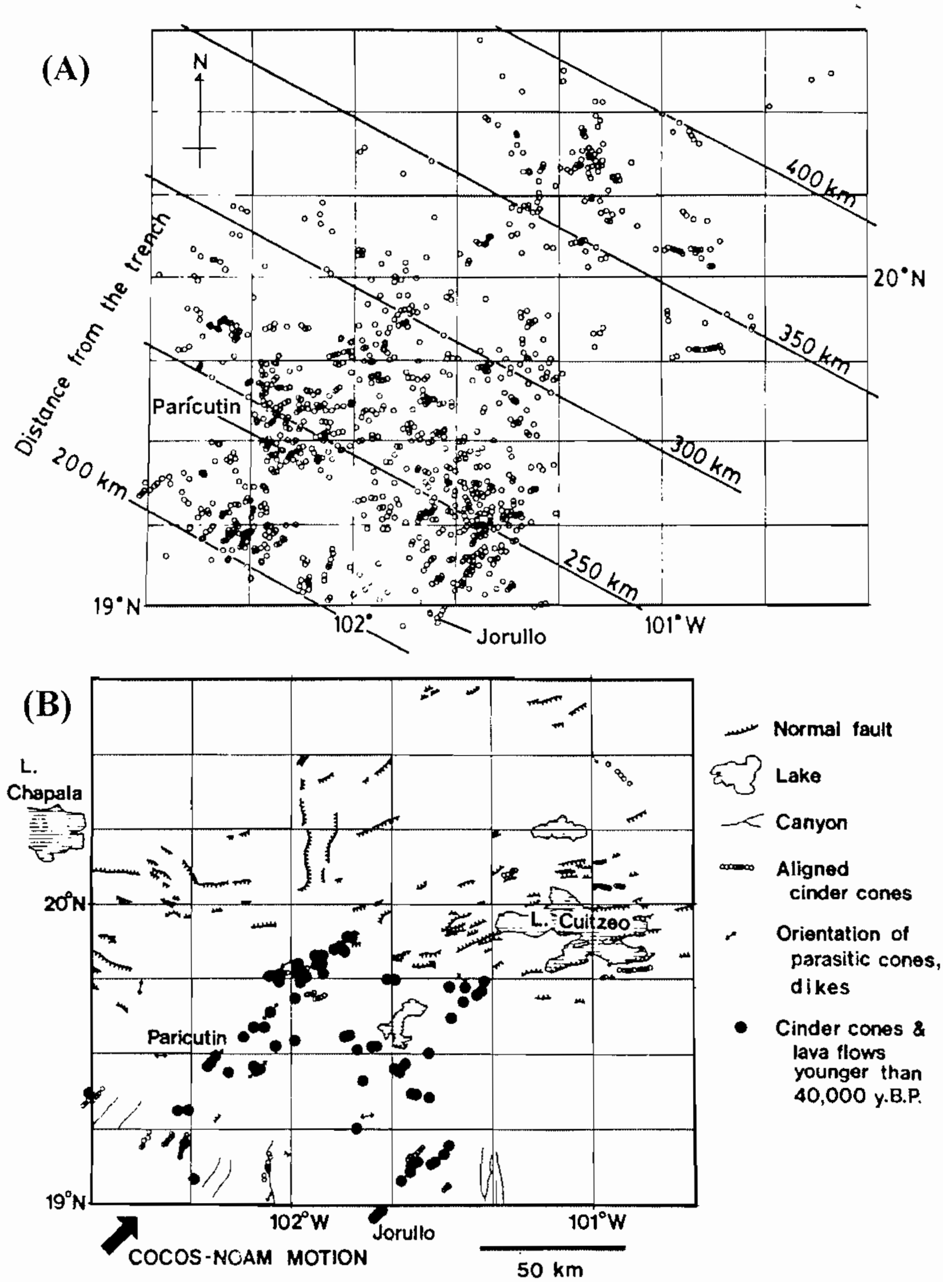


Fig. 14. (A) Distribution of volcanoes in the Michoacán-Guanajuato Volcanic Field (reproduced from Hasenaka and Carmichael, 1985a). Lines indicate distance from the Middle America Trench. The positions of Parícutin and Jorullo are indicated. (B) Alignments of cinder cones, their vents and dikes, and normal faults in the Michoacán-Guanajuato Volcanic Field (reproduced from Hasenaka and Carmichael, 1985a). Large dots indicate cinder cones and lava flows younger than 40,000 years. Arrow shows the motion vector of the Cocos Plate relative to the North American Plate.

Jorullo Volcano (1759-1774)

The story of the Jorullo eruption was in a state of great confusion for many years, confusion stemming partly form the delayed publication of an eye-witness report to the Spanish Viceroy concerning the early activity, and partly from the erroneous observations of Alexander von Humboldt (1810), who visited the area in 1803. Inspired by the incorrect *craters of elevation* theory of his friend von Buch, von Humboldt wrongly interpreted the Jorullo lava field as a large volcanic blister that rose from the ground. Gadow (1930) gave an insightful account of the eruption and English translations of all important prior observations as a preface to his study of floral and faunal reclamation of the devastated area.

Prior to 1759, the area was a cultivated, west-sloping basin bounded by steeply dissected escarpments of Cenozoic intrusives, tuffs, and lavas. The area has a tropical climate and a general elevation of 600 to 800 m. Famous for its fertility, the land was known as Jorullo, or *Paradise*, in the Tarascan Indian language. Hacienda de Jorullo was situated near Cerro Partido, which rose as an E-W-trending ridge near the basin center (Figs. 15 and 16A). At the eastern end of the basin was the narrow and deep ravine of Cuitinga Creek, which followed a NE to SW course before turning west along the granite ridge forming the southern boundary of the basin.

Subterranean noises were first heard in late June of 1759, increasing to the level of cannon shots by September 17. Earthquakes badly damaged structures on the Hacienda. On the morning of September 29, several sharp tremors were felt, and a dense dark cloud issued from the Cuitinga Creek just SE of the Hacienda. The early part of the eruption was characterized by phreatic and phreatomagmatic activity, which blanketed the surrounding area with a sticky mud. Gadow (1930) noted that despite a near absence of precipitation in the fall of 1759, large quantities of water and mud were flowing from the Jorullo area. Numerous springs became active in the surrounding hills, and streams alternated between swollen and dry. Sáyago, the administrator of Hacienda de Jorullo, described pulses of hot muddy water pouring from small short-lived vents. Ash falls covered the surrounding area and by October 6 the town of La Huacana, 9 km to the west (Fig. 15), was abandoned. Streams choked with ash flooded much of the valley to the west of the volcano, from La Puerta de la Playa to La Huacana (Fig. 15). The copious outflow of water in the early stages of the eruption probably resulted from the outward migration of groundwater ahead of the rising magma body as suggested for the 1902 eruption of Mt. Pelee (Roobol and Smith, 1975; Fisher and Heiken, 1982). The first incandescent bombs were noted on October 8, and by October 14 phreatic aspects of the

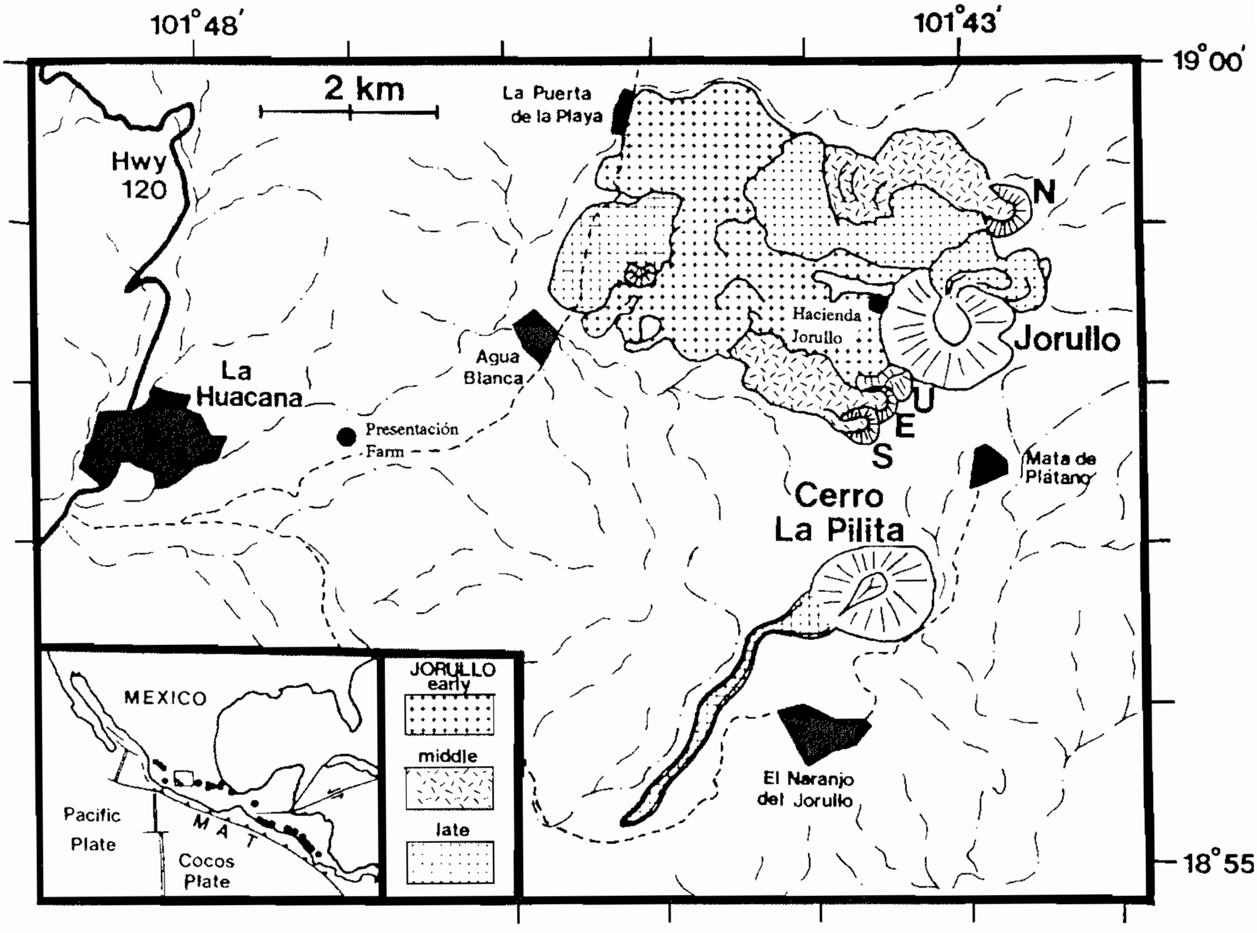


Fig. 15. Location map showing Jorullo volcano, its four parasitic cones (N = Volcán del Norte, U = unnamed, E = Volcán de Enmedio, S = Volcán del Sur), and the three stages of lava flows (see pattern key). The former locations of Hacienda de Jorullo and Presentación Farm are indicated. Cerro la Pilita is a pre-historical lamprophyric cinder cone with lava flow centered 3 km SSE of Jorullo. Cities and villages are shown in black. Dashed lines are unpaved roads. Dot-dash lines show drainages. On inset map, small square outlines the Michoacán-Guanajuato Volcanic Field, stars show Paricutin and Jorullo, dots represent major composite volcanoes, and MAT = Middle America Trench.

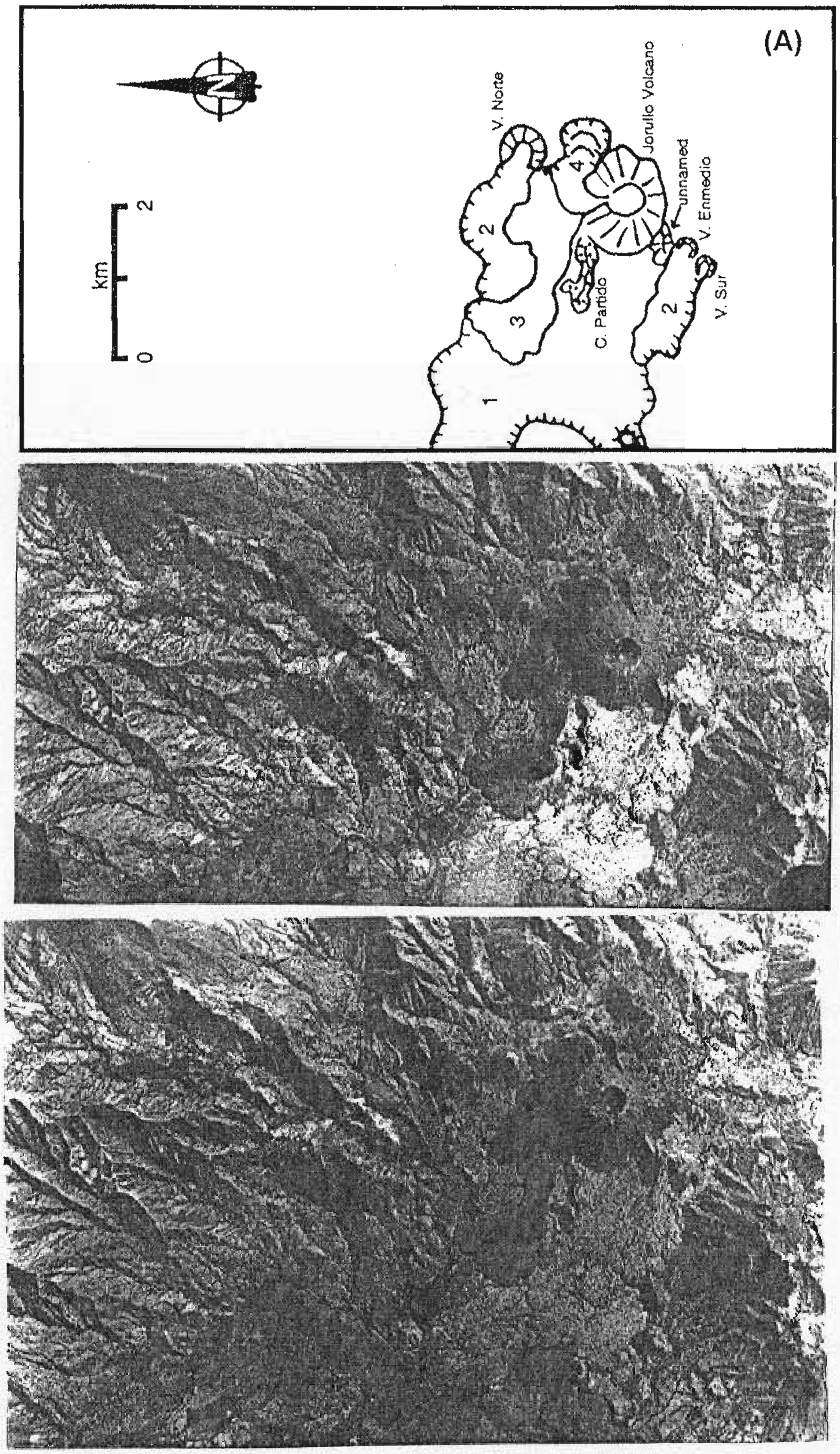
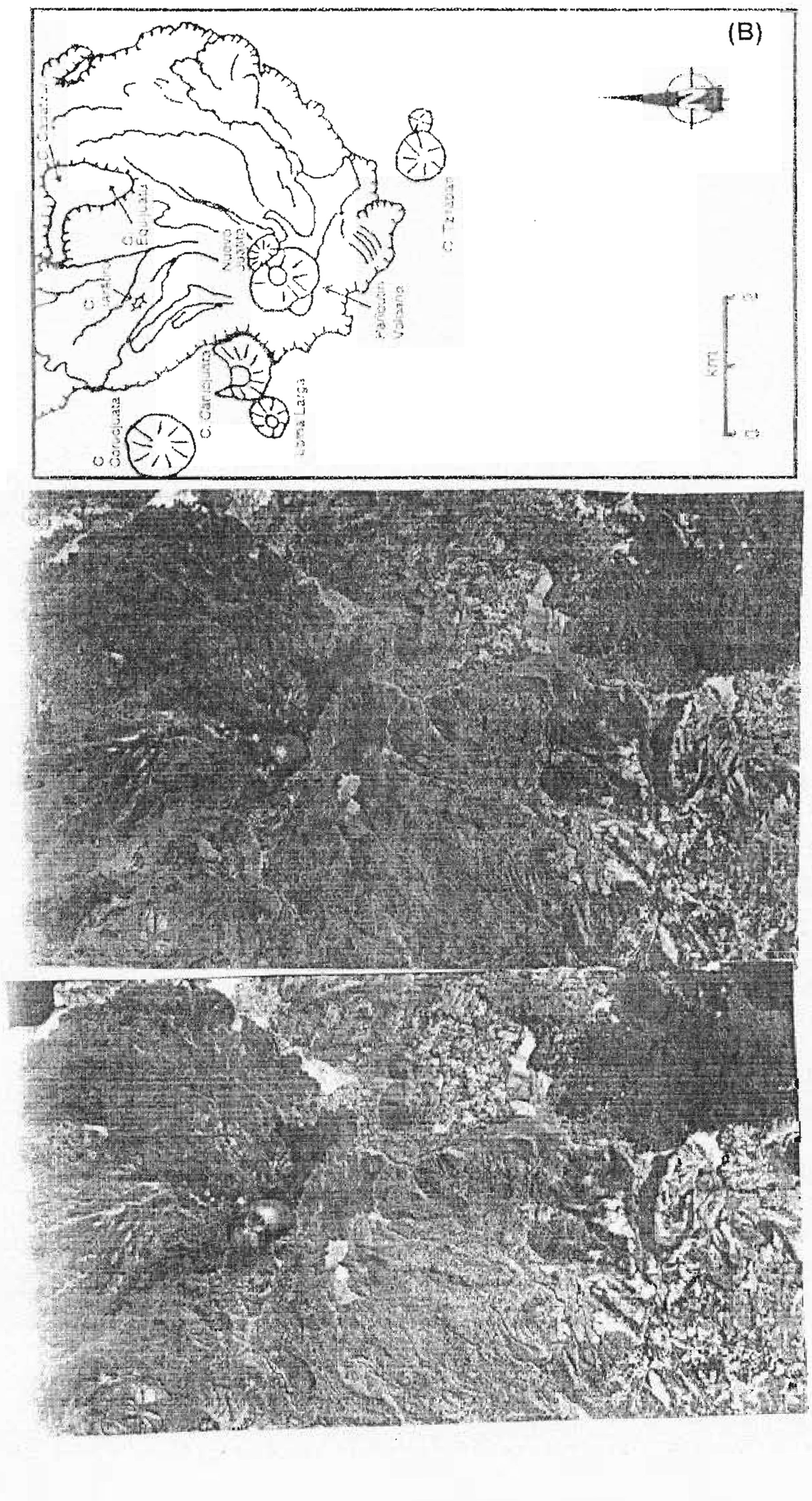


Fig. 16. (A) Stereographic airphoto pair of Jorullo volcano. The main cone is flanked by four parasitic vents aligned NE-SW. Four different stages of lavas are indicated by numbers 1 (oldest) to 4 (youngest). Cerro Partido is an elevated ridge of volcanic basement that was surrounded by the Jorullo lavas. Hachures mark the margins of the lava field. (B) Stereographic airphoto pair of Parícutin volcano as it appeard in the early 1970s. The NE-flank vent mound of Nuevo Juatita is labeled along with the small remaining remnant of the older Cerro de Jarátiro. Other older volcanoes are also labeled: Cerro de Capatzun, Cerro de Equijauta, Cerro de Corucjuata, Cerro de Canicjuata, Loma Larga, and Cerro de Tzirapan. Hachures mark the margins of the lava field.


(B)
km

eruption declined in significance as it became dominantly magmatic in character. Water and mud were no longer reported as issuing from the ground. The second and final report of Sáyago was written on November 13, by which time the main cone of Jorullo had reached 250 m in height. No lava had emerged by this date, after which there is unfortunately little reliable reporting. Oral traditions refer to violent eruptions through 1764, the year of greatest activity, and lesser eruptions until 1774. A report for the new Governor in 1766 describes a scene similar to that of today (Figs. 15, 16A, and 17), and Gadow argues that the majority of the lavas had erupted by that date, probably between 1760 and 1766.

Magma and gas issued from a NE-SW-trending line of five cinder and lava cones separated by 3 km along the course of the Cuitinga Creek (Figs. 15 and 16A): the large main cone of Jorullo, a single breached cone to its NE (Volcán del Norte), and three breached cones to its SW (unnamed, Volcán de Enmedio, Volcán del Sur). The main cone dwarfs the satellite cones in size and appears to differ from them structurally in being a composite cone of lava as well as cinder. The vents are oriented about N35°E, sub-parallel to many other cinder-cone alignments in the southern Michoacán-Guanajuato Volcanic Field (Fig. 14), including the vent alignment at Parícutin, and to the relative-motion vector for the Cocos and North American Plates (Minster and Jordan, 1978). This orientation is presumably perpendicular to the minimum horizontal compressive stress direction in the area (Nakamura, 1977). Early workers identified four to six different lava flows at Jorullo (Gadow, 1930). Three lava stages or groups are recognized in this study: early, middle, and late (Fig. 15), but the late group can itself be divided, distinguishing the last dark unvegetated lava tongue (Figs. 16A and 17). This is the only lava to have emerged following the late-stage cessation of tephra deposition; thus it did not receive an infilling layer of fine tephra that could rapidly weather to begin supporting vegetation.

At both Jorullo and Parícutin, the early lavas were the poorest in silica and the most fluid; they largely defined the final extent of the ground covered, with succeeding, more-viscous lavas generally forming thicker terraced flows upon them. The Jorullo flows consist primarily of block lava and usually have prominent levees. The early lavas issued from an unknown point, probably near the base of the main cone, and descended the gentle gradient of the basin to the west, covering 9 km^2 of the former fertile valley, an area since called *Malpais* (badlands). Next came the middle-stage lavas, which breached the western sides of the northern and southern satellite cones. The downhill, westward flow of lava kept the western sides of these cones open, resulting in crescentic morphologies, similar in form to the Sapichu vent at Parícutin, which was active during 1943-1944. The late-stage lavas issued from the northern side of the main cone. Pyroclastic activity continued through the extrusion of most late-stage lavas, and almost all lava flows were covered by ash-fall layers. Following the end of pyroclastic activity, a small lava tongue then emerged from the main cone, bringing the eruption of Jorullo to a close. This black, youngest lava flow (Figs. 16A and 17) is still relatively unvegetated today and stands in sharp visual contrast to the subdued hues of the slightly older, but ash-covered lavas, where vegetation found an easy foothold. Since the end of the eruption, the crater has been collapsing inward along arcuate step faults, increasing both the crater diameter (400 × 500 m) and its depth (150 m).

The main cone of Jorullo rises some 350 m above its surroundings to an elevation of 1,220 m. It has a volume of approximately 0.20 km^3 and the smaller parasitic cones have a combined volume of 0.05 km^3. The lavas have an estimated volume of 0.50 km^3, although this figure is made uncertain by a lack of information on the depth of lava close to the vent. The volume of ash-fall deposits is unknown. By analogy with Parícutin, which produced 0.49 km^3 of magma as lavas and 0.83 km^3 of magma as tephra (Fries, 1953), the pyroclastic deposits of Jorullo may have represented up to 1.25 km^3 of magma. The total mass of magma erupted at Jorullo, therefore, was possibly 2 km^3.

Interestingly, the Jorullo eruption followed the unusual pattern of the Parícutin activity in that magmas became richer in SiO_2 as time progressed (Luhr and Carmichael, 1985). The extensive early lavas are primitive basalts, with Mg# = 73, 260 ppm Ni, and 515 ppm Cr; they have vol% olivine phenocrysts (plus Cr-spinel inclusions). These evolved systematically with time toward differentiated orthopyroxene- and hornblende-bearing basaltic andesites, poorer in MgO, FeO^T, CaO, Cr, Co, and Ni, and richer in SiO_2, Al_2O_3, K_2O, Sr, Ba, and other incompatible elements (Fig. 18). As shown in Fig. 18, the most differentiated, late-stage Jorullo magmas are similar to the most primitive, early Parícutin magmas. Thus, the two suites of magmas erupted during historical times in the Michoacán-Guanajuato Volcanic Field together define a continuous differentiation sequence from primitive basalt to andesite.

Just 3 km SW of Jorullo lies Cerro la Pilita, a late-Pleistocene cinder cone that sent a lava flow 3 km down a ravine to the SW. Pilita and Jorullo lie along the same NE-SW alignment of volcanic centers (Figs. 14A and 15). Unlike the calc-alkaline basalts and basaltic andesites erupted from Jorullo, however, the rocks of La Pilita are hornblende trachybasalts, with strong enrichments in K, P, Ba, Sr, La, and other incompatible elements (Luhr and Carmichael, 1985). These are lamprophyric in many senses, but the do not qualify on petrographic grounds, having a few percent plagioclase

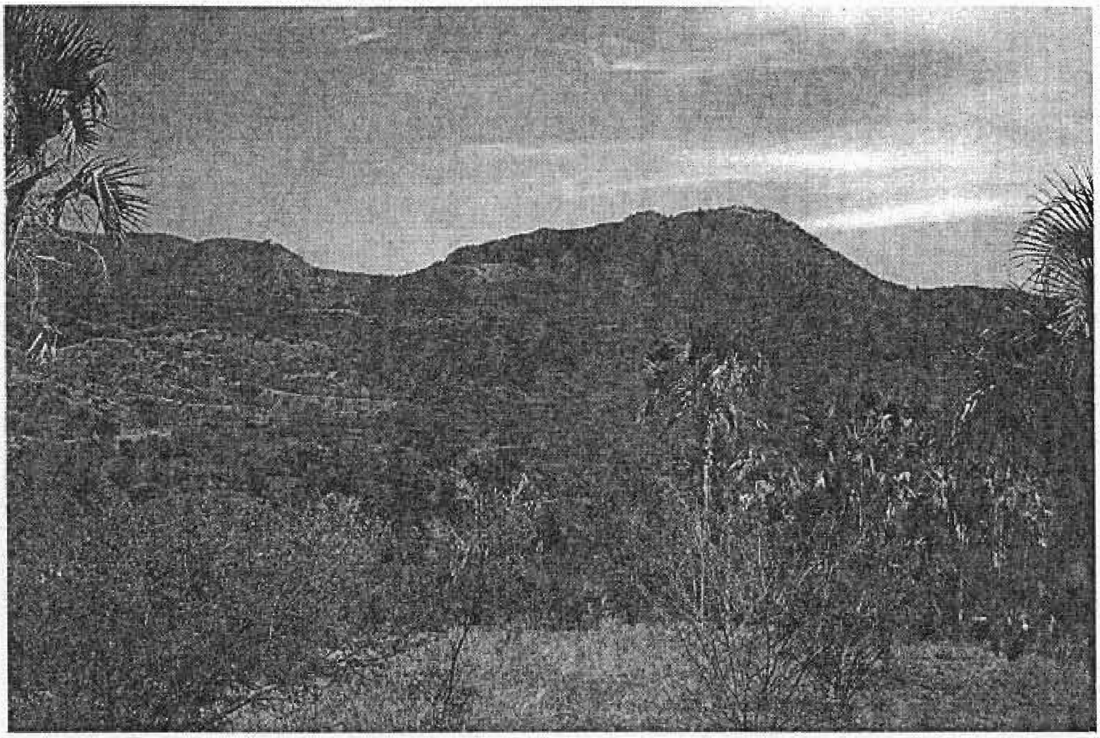


Fig. 17. Jorullo volcano was born in 1759 and erupted for 15 years. It lies 81 km SE of Parícutin, the youngest volcano in the Michoacán-Guanajuato Volcanic Field. In this view from the NW, the final black tongue of unvegetated lava that flowed north from the crater rim is visible on the center horizon. One of Jorullo's four parasitic cones, Volcán del Norte, is near the photo's left margin.

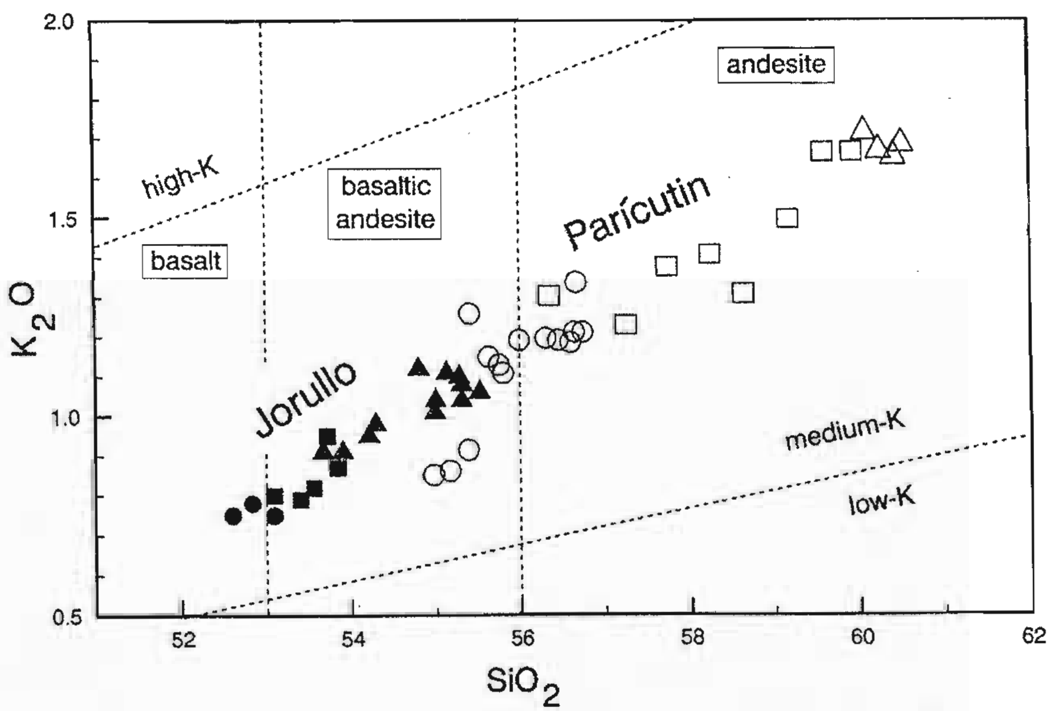


Fig. 18. Whole-rock compositions of lavas from Jorullo (solid symbols: data from Luhr and Carmichael, 1985) and Parícutin (open symbols: data from Wilcox, 1954, and McBirney et al., 1987). The suites are divided into early (circles), middle (squares), and late (triangles) stages. For Jorullo, the stages are divided as discussed in the text and shown on Fig. 15. For Parícutin we have divided the samples based on year of eruption: early (1943-1945), middle (1946-1949), late (1950-1952). The boundaries separating low-K, medium-K, and high-K suites are taken from Gill (1981).

phenocrysts (0.3 mm). Nonetheless, the Jorullo-La Pilita pairing is closely equivalent to the contemporaneous eruptions of calc-alkaline and lamprophyric magmas at other fields in the western Trans-Mexican Volcanic Belt: Mascota, Los Volcanes, San Sebastian, and Colima.

Parícutin Volcano (1943-1952)

We expect to land at Uruapan at about 10 AM. From Uruapan airport we will proceed by vans to Parícutin volcano. The airport is located 2 km SE of downtown Uruapan. We will circle the city and head north on Hwy. 37 (see Fig. 19). Five km beyond Uruapan we will be able to see Paracho volcano to the NNE. Paracho has been described as a shield volcano capped by a lava cone (Hasenaka, 1992). However, recent mapping has revealed a more complex structure. Paracho appears to be a composite volcano, with lava flows, tephra-fall deposits, pyroclastic-flow deposits, and laharic deposits. The lava cone at its summit marks the last eruptive event. Paracho volcano poses a threat to the city of the same name, which is famous for its high quality guitars.

Ten km north of Uruapan we will turn west toward Angahuan and Parícutin Volcano (Fig. 16B). This road passes by several small-sized volcanic cones (Fig. 19). About 17 km from this junction we'll turn south on a recently constructed dirt road (Fig. 20) to the church of San Juan Parangaricutiro, which was surrounded by lava in July, 1944 (fronticepiece).

FIELD EXCURSION TO PARÍCUTIN VOLCANO

Many of the passages below are reprinted from original studies by Foshag and González-Reyna (1956) and Nolan (1979), which were earlier reprinted in Luhr and Simkin (1993).

Stop 1 (19.529°N, 102.208°W): Distal ash-fall deposits.

During the first year of the eruption (1943), ashes from Parícutin reached their greatest distance, falling on Morelia (125 km ENE) and Mexico City (320 km east). The towns and villages most affected by ash falls, though, were those within 25 km of the vent. Over much of this area, the total ash thickness was not great; the 25-cm isopach extended less than 10 km from the volcano (Segerstrom, 1950). Most of this ash has been stripped away in the 54 years since the eruption began. Today, ash-fall deposits can only be seen less than 6 km from the vent.

At this stop, we can observe a 55-cm-thick layered sequence of ashes. Much of this sequence has been

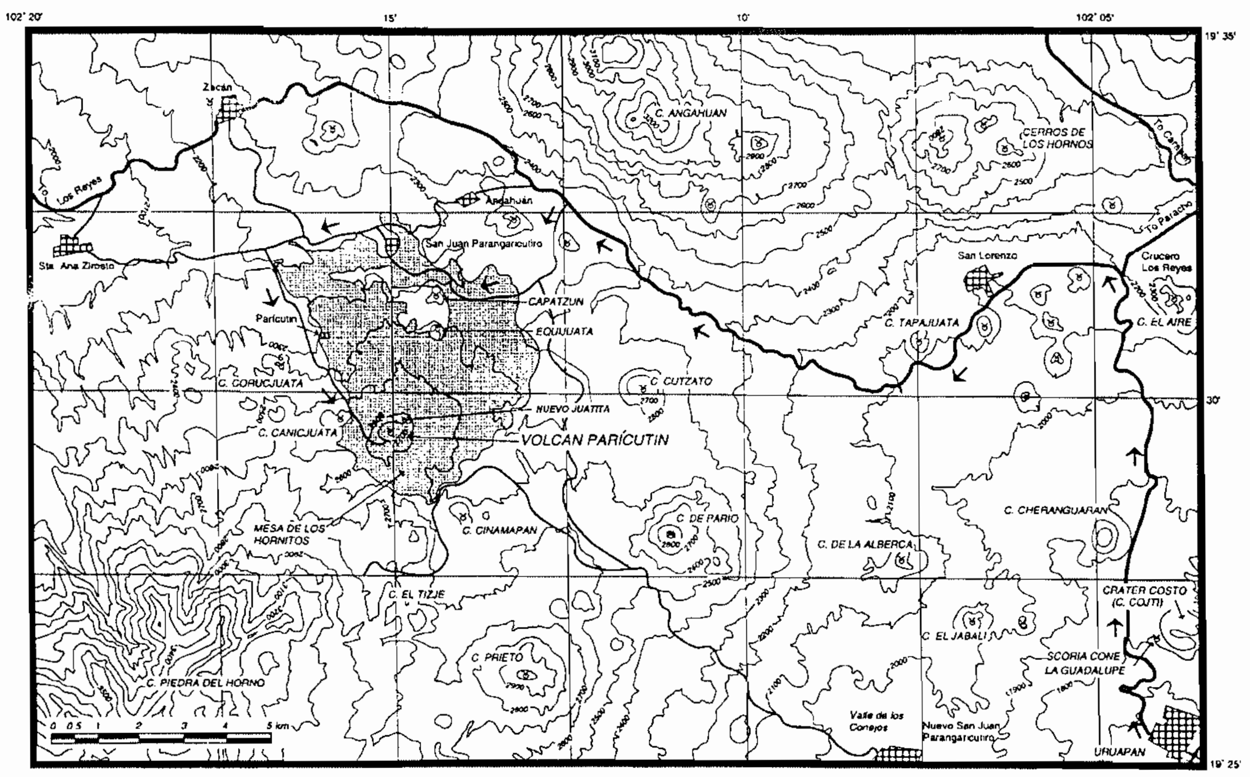


Fig. 19. Regional location map for Parícutin volcano. The arrows indicate the route from Uruapan airport to the volcano. Current and pre-eruption towns and villages are shown along with the main topographic features of the region (contours in meters). Most of the hills are cinder cones.

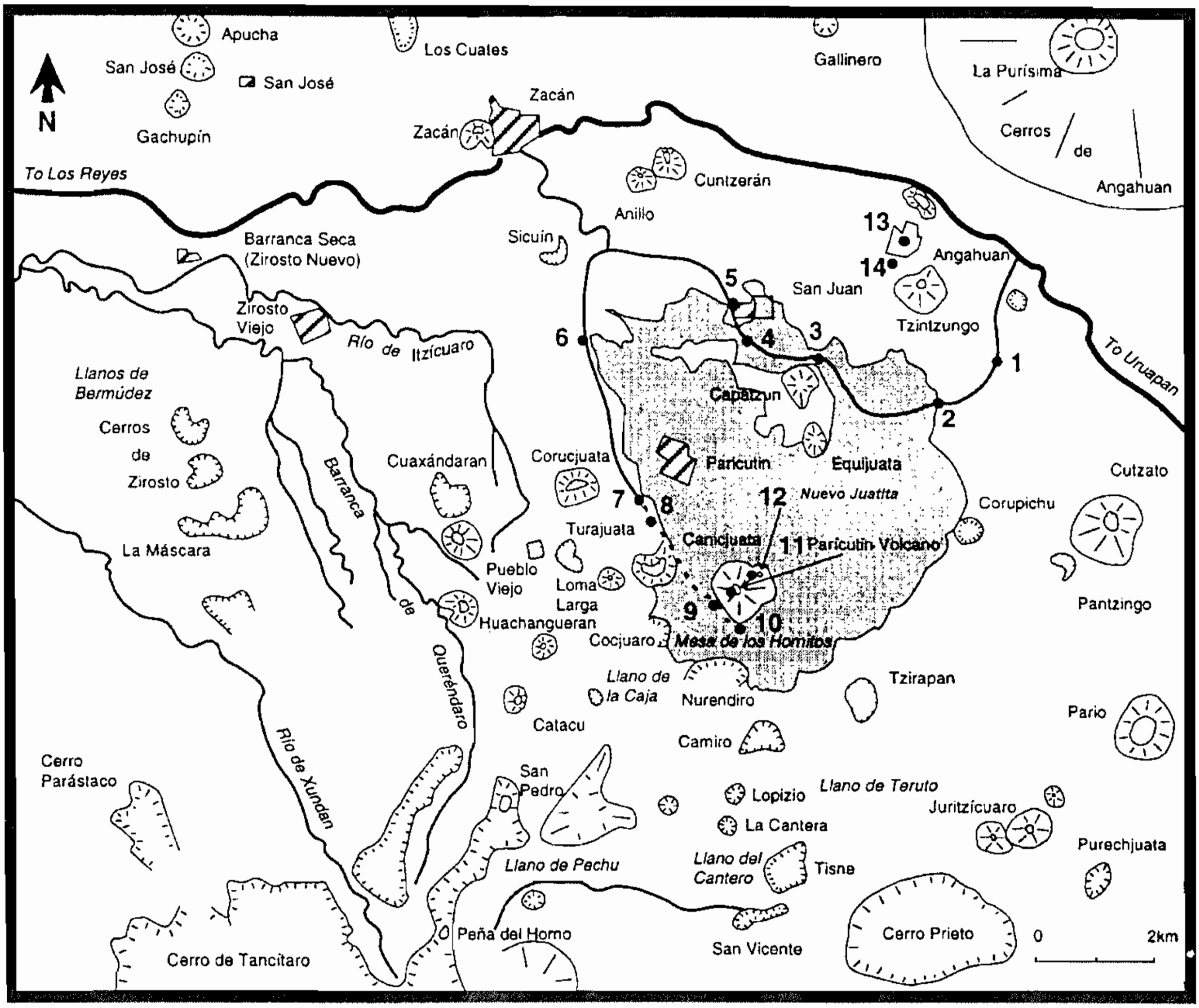


Fig. 20. Local location map for Parícutin volcano and vicinity. The Parícutin lava field is shown in gray. The fieldtrip stops are numbered.

reworked by local farmers during plowing and fence construction. It also shows crossbedding due to fluvial transport. In addition to the dark-gray ashes from Parícutin, the deposit also includes reworked fragments from nearby pre-historical cones.

Stop 2 (19.518°N, 102.221°W): Eastern border of the Parícutin lava field, 2.5 km from the Uruapan highway.

The lavas from Parícutin began to flow on the second day of the eruption (February 21, 1943, at 11:00). The lavas of the first stage (Quitzocho lavas) moved towards the NE. They stopped on October 18, 1943, without reaching this point. Lavas from the Sapichu vent, at the NE foot of the cone, started to flow on October 18, 1943, and reached a place close to here in December, 1943. The Taquí lavas then began to erupt from a vent at the SW base of the cone on January 8, 1944. These lavas moved eastward around the south base of the cone and then northward over the next 4 months. In April, renewed activity, described below for Site 3, caused the flow front to advance rapidly through this area, building the section of the lava field we see at this stop. By April 24, 1944, the Taquí lavas reached the old road from San Juan Parangaricutiro to Uruapan, and then continued toward San Juan. They are commonly called the San Juan lavas since these flows were responsible for the destruction of San Juan Parangaricutiro.

From the dirt road we can observe the marginal levees of the San Juan lava flows. Here we can also see mudflow deposits that overlie the lava levees. Segerstrom (1960) described various efforts by local farmers to divert flood waters moving northward along the eastern edge of the Parícutin lava field. In 1957 at this point he observed a rock dam, 65 m long, 1.5 m wide, and 2 m high, that farmers used to divert floodwaters to the NW, so that they poured into a low part of the San Juan lava field. It was hoped that this area could be cultivated in the near future. The mudflow deposits we see at this stop are probably a consequence of that effort.

The San Juan lava at the edge of the Parícutin field has a thickness of less than 5 meters and a very vesicular texture. Individual flow units have levees up to 10 meters high and lower central portions. The dirt road was partly cut through the San Juan lava here, thus providing an excellent place to collect fresh rock samples (Fig. 21). These flows are a combination of block and aa lava, very scoriaceous, showing olivine and occasional plagioclase phenocrysts.

As it continues westward toward San Juan Parangaricutiro, the new dirt road follows about the same trend as the old road from Uruapan. From this point Parícutin volcano can be seen in the background; at its NE base is the parasitic cone Nuevo Juatita, which was a main source of lava from Jan. 19, 1947 until the end of the eruption in 1952. Nuevo Juatita, whose summit is covered with sulfur and other fumarolic minerals, lies at about the same site as the older parasitic cone Sapichu.

Stop 3 (19.524°N, 102.230°W): Levees of the San Juan lavas bordering Cerro de Equijuata and Cerro de Capatzún; emergent lava streams at the bottom of large levees.

From its outbreak on January 8, 1944 along the SW base of the cone, until early April, the Taquí lava had reached the E base of Cerro de Equijuata, 2½ km NNE of the crater (Fig. 19). Its advance had essentially ceased, but two weeks later, on April 14, new lava burst forth from the top of the Taquí lava flow, issuing from tubes and tunnels within the seemingly stagnant flow that had hidden its progress. The new Taquí flow lobes moved rapidly to the north, burying the road from San Juan Parangaricutiro to Uruapan by April 24. One of the lava streams flowed as fast as 180 m/hr (the fastest lava velocity recorded for the eruption). The lavas then turned NW toward San Juan Parangaricutiro. They followed the narrow valley of Juanantacua (in which the road was nested) limited by the steep slopes of Cerro Capatzún to the south (Fig. 20). In late April the lavas completely filled the valley, and they came to rest in the cemetery at the edge of San Juan Parangaricutiro in early May. These lavas were more scoriaceous and less blocky than the previous ones.

Fig. 21. Roadcut through a small lava levee at Stop 2. Notice the flat but rugged area of aa-type Taquí lava flows in the background. This is a good site to get a fresh sample from the core of the levee.

Approaching Stop 3 we will travel across the San Juan lava, toward the partly buried town. At this stop we will have a look at the levee formed on the flow margins as it encountered the obstacle of Cerro de Capatzún. Levees bordering Capatzún and Cerro de Equijuata to its south can exceed 50 m in height. Some of the lava emerged from tubes at the base of flow fronts, as can be seen here (Fig. 22).

Stop 4 (19.530°N, 102.250°W): Feeding lava tube.

The Taquí lava front stagnated for about a month at the edge of San Juan Parangaricutiro before resuming its advance, and on June 17 began to invade the town itself. The flow moved down Arroyo Principal at the eastern edge of the town, and spreading laterally when the arroyo was filled, soon reached the first street. The new advance of lava showed distinct differences both in character of movement and in structure from previous flows. The advance of the lava down Arroyo Principal was rather rapid; the lateral spread was at a rate of 1 to 2 m/hr. But instead of advancing as a moving front of rubble, the lava moved as distinct and independent lobes. At intervals along and usually halfway up the lava face, viscous lava broke out in tongues. The movement of the lobes persisted for less than a day, when they congealed; and the intervening sectors put out other lobes. These lobes sometimes issued from distinct orifices, yielding rough tongues suggesting toothpaste squeezed from a tube.

The new road along which we will travel has exposed fascinating features, like lava tubes, not easily seen before due to the inaccessibility of the middle part

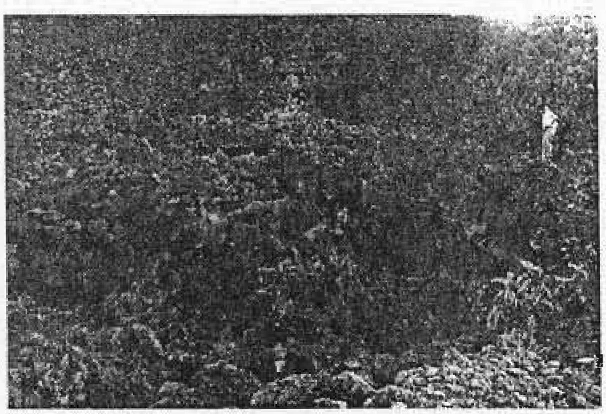


Fig. 22. Emergent lava streams at the base of large levees where lava flows banked against Cerro de Capatzún (Stop 3).

of the Parícutin lava field. Construction of the road exposed a lava tube about 4 m beneath the surface. Lava stalactites are visible on the tube roof, and a solidified lava stream forms the floor (Figs. 23 and 24).

Stop 5 (19.534°N, 102.248°W): The church of San Juan Parangaricutiro.

The main body of the Taquí flow (from here referred as the San Juan flow) advanced into the town of San Juan Parangaricutiro, yielding not so much the clinkery blocky surface of the earlier flows, but huge torn and slaggy masses. Torn and striated blocks commonly rose and showed a grooved, or harsh surface. The creaking of the moving blocks was frequently heard.

The advancing tongue as it flowed down the steep and narrow Arroyo Principal, frequently showed remarkable fluidity. At a point about 1 km SE of San Juan Parangaricutiro, the flow advanced down the arroyo as a steep front at a rate of 40 m/hr. Almost the entire front, confined by the steep high walls of the arroyo was incandescent. Considering that this magma had probably issued from the Taquí vents some 6 months earlier, and had already traveled in lava tubes 8 km to the north, the retention of its heat and power to advance seem remarkable.

In March, 1944, the people of San Juan Parangaricutiro agreed to stay until lava reached the cemetery, which finally happened in early May. The steady and inexorable advance of the lava finally convinced the remaining inhabitants of San Juan Parangaricutiro that they must evacuate their town. Because of their deep attachment to soil, many remained until the lava covered the last small corner of their land, then sadly departed by the trucks the government placed at their disposal. With the destruction of the church, the strongest tie that bound them to the place was broken. The people moved from the town and founded a new one 15 km SE of this place. On May 8 the bishop, having arrived from the city of Zamora the previous day, celebrated the final mass in the unfinished church of San Juan Parangaricutiro. The next day, the bishop lifted the sacred image of El Señor de Los Milagros from the church altar and led the evacuation procession. The people walked for 3 days, along roads lined with crowds that provided food and water for the bearers of El Señor de Los Milagros. The crowds were particularly large and enthusiastic in Uruapan. On May 11 the people reached their new home, about 10 km SE of the new volcano; they later named it Nuevo San Juan Parangaricutiro. The people of new San Juan have built a grand church to house El Señor de los Milagros. This has become an important site for Catholic pilgrims from Mexico and other lands, and an important source of revenue for this thriving town. By mid-July all but a few outlying squares at the western edge of the town were covered by lava. Of the church only the 23-m-high tower, and its unfinished twin projected above the torn lava surface.

From this point, the buried church of San Juan Parangaricutiro can be seen to the SE (Fig. 25). The high tower (NE corner of the church) is perfectly seen from the distance and sometimes the incomplete tower (SW corner) can also be seen. The apse, where the altar with El Señor resided, was at the SE end, the first to be engulfed by lava (Fig. 26).

Stop 6 (19.530°N, 102.277°W): Distal ash-fall deposits from Parícutin volcano overlying pre-existing soils.

A few days after June 17, 1944, when the San Juan flow first invaded the town, a number of distinct lava streams broke forth from the summit of the lava flow near its farthest advance, moved rapidly down the flanks in radial incandescent streams, and then spread out in a single night into a fan-shaped mass, covering 350,000 m^2 of terrain at Llano Huirambosta, 2 km beyond San Juan Parangaricutiro. By early August the lava tongue of San Juan Parangaricutiro had entirely ceased its movement, its ultimate advance reaching Llano Huirambosta, where the arroyos from Parícutin and San Juan Parangaricutiro

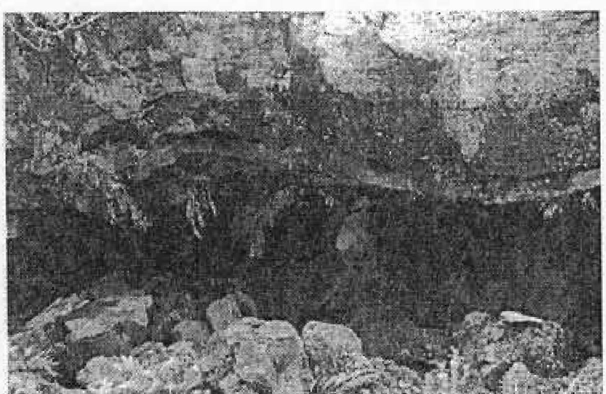


Fig. 23. Lava tube in Taquí flow at Stop 4.

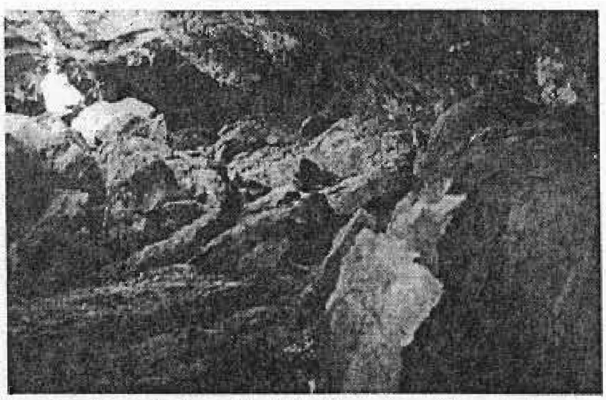


Fig. 24. Internal view of the Taquí lava tube at Stop 4, showing the congealed lava stream on its floor.

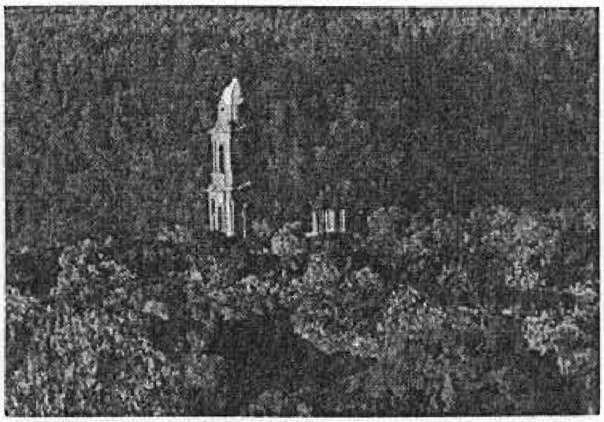


Fig. 25. View of the church of San Juan Parangaricutiro from the west at Stop 5. Only one of the church's two towers had been completed when the eruption of Parícutin forced abandonment of the town.

Fig. 26. The apse of the church of San Juan Parangaricutiro, which was the first part to be surrounded and invaded by San Juan (Taquí) lavas (Stop 5).

joined. The Taquí vent continued to yield abundant lava, which sometime during late July and early August, instead of finding its way through subsurface channels to the San Juan flow, advanced as a sheet from an undetermined point overriding the previous flows around the base of the cone. On September 27, 1944, lava from the Taquí vents, after having flowed for more than 8 months around the south and east sides of the base of the cone, began flowing directly north on the cone's west side, following Arroyo de Parícutin and filling the valley between the first Parícutin flow and Cerro de Canicjuata. Upon reaching the flatter terrain about Parícutin village, it spread laterally and covered the site of that unfortunate ash-buried town. Continuing along Arroyo de Parícutin, it invaded Llano de Huirambosta and on October 20 finally joined the Parangaricutiro tongue near the end of its course. The town of Parícutin was not completely buried by Taquí flows. On March 7, 1945, the job was almost completed by lavas from a new vent at the SW base of the cone. Finally, by January 28, 1946, the last vestiges of Parícutin village were buried by lavas coming from Mesa de Los Hornitos, also at the SW base of the volcano.

On the way from Stop 5 to Stop 6 we will be bordering Llano de Huirambosta. At Stop 6 we will have the opportunity to see the Taquí lavas that flowed through Arroyo de Parícutin, then follow them all the way to Stop 7.

Stop 6 is located approximately 5 km northwest of Parícutin's crater. We can see here a 1.4-m-thick stratified sequence of ash and lapilli (mm in diameter), with some laminated parts, overlying the previous soil. The deposit mainly shows normal grading, but some examples of reverse grading are evident. Most of the clasts are subangular. The laminated layers show slight cross bedding due to wind transport during deposition (Fig. 27). These ash- and lapilli-fall deposits are very similar to those that buried Parícutin village, which lies beneath lava about 2 km closer to the volcano (Fig. 20). Only a sign visible from the road indicates its location.

Stop 7 (19.512°N, 102.269°W): Foothills of Corucjuata volcano.

At this site we will leave the vans in order to walk towards the main cone of Parícutin, whose base lies ~2 km to the SE. For those who prefer to ride a horse (Fig. 28) rather than walk there will be local people waiting here with horses to rent. The altitude here is about 2,500 m.a.s.l. (about 8,200 ft.). The walk is rather tiring because it is made through loose ashes.

Stop 8 (19.504°N, 102.262°W): Sequence of reworked material from Parícutin and Canicjuata volcanoes.

As we approach Parícutin volcano, the ash layers become thicker. However, not all these deposits show primary ash-fall structures. Most of these ashes have been reworked by wind and water. At this site, nearly 2 m of ash is exposed showing cross bedding and a heterogeneous rounded-subrounded clast composition.

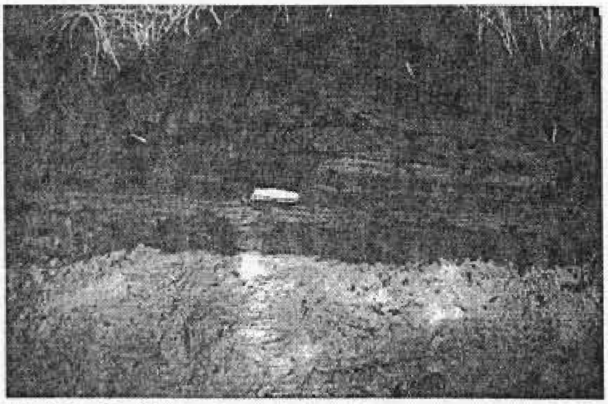


Fig. 27. Stratified ash- and lapilli-fall sequence, 1.4 m thick, above pre-existing soil. This medial facies exposure is located 5 km NW of Parícutin's crater (Stop 6).

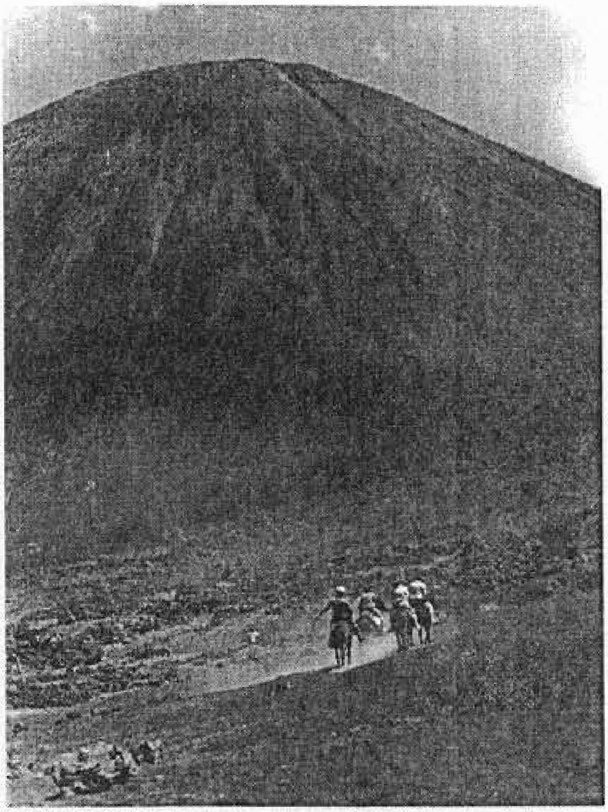


Fig. 28. Riding horses towards Parícutin volcano, between Stops 7 and 9, along the foothills on the NE side of Canicjuata volcano.

These layers include ash and lapilli from both Parícutin and Canicjuata; the latter fragments are light brown in color and contrast with the darker Parícutin fragments.

Stop 9 (19.494°N, 102.256°W): Proximal scoria- and ash-fall facies of Parícutin volcano.

Earthquakes began to be felt in the region of Parícutin and San Juan Parangaricutiro in January, 1943, and increased in number and intensity through mid February. On February 20 at about 16:00, Parícutin volcano was born at the Cuiyusuru farm. The birth was observed by the owner, Dionisio Pulido, and his family, Tarascan indians who lived in the nearby village of Parícutin. Pulido heard a thunderous noise and soon noticed a newly opened fissure (30 m east-west) through a knoll with a small pre-existing depression. He noticed that ground in the depression rose 2-2½ m and began to eject "smoke or dust, gray like ashes". The smell of sulfur and loud and continuous whistling and hissing noises accompanied increased ash emission as Pulido and his family fled. A team of people from San Juan Parangaricutiro arrived at the site at 18:00 and saw a trench-like fissure, a hole, and projectiles sent to a height of 5 m; there were low mounds of fine ash along the trench, and "boiling sand" in the vent itself. They witnessed the opening of a new fissure, widening the orifice to 2 m diameter and increasing the size of the eruptive column. Jesús Anguiano and Jesús Martínez, members of this investigation party, collected rock and ash specimens. At the end of this day, the cone was estimated to be 6 m high. A week later the cone height was 106 m, after a month 148 m, and after a year 336 m. The final cone height was estimated at 424 m on May 1, 1952.

Following the trail we will reach Stop 9 at the edge of the lava plateau named "Mesa de los Hornitos". Here at the base of the Parícutin cone we can find several bombs or fragments of bombs that rolled down the cone slope after flying through the air. On one side of the trail we will find a scarp cut through the proximal deposits of the main cone. This sequence consists of 2.2 m of alternating ash and lapilli layers, with some bomb sags evident (Fig. 29). The clasts are mainly angular scoria, but unbroken bombs can be found in the area. Some of the ash layers show cross bedding due to wind transport.

Stop 10 (19.490°N, 102.256°W): Mesa de los Hornitos.

By the end of 1943, Ezequiel Ordóñez noticed the appearance of steeply conical peaks with vertical shaft-like craters on the surfaces of lava flows near the base of the new volcano. He named these "volcancitos" (little volcanoes). In February 1944, the congealed surfaces of lava flows issuing from the Taquí vents at the SW foot of the main cone showed a great number of low irregular pinnacles of vesicular lava, which Ordóñez (1943) named "hornitos" (little furnaces). Foshag and González-Reyna (1956) described bluish vapors rising from summit vents on "volcancitos", the irregular openings in "hornitos", and fissures in the lavas. A strong odor of hydrochloric acid pervaded the vicinity, and loud hissing noises due to the escape of gases from several

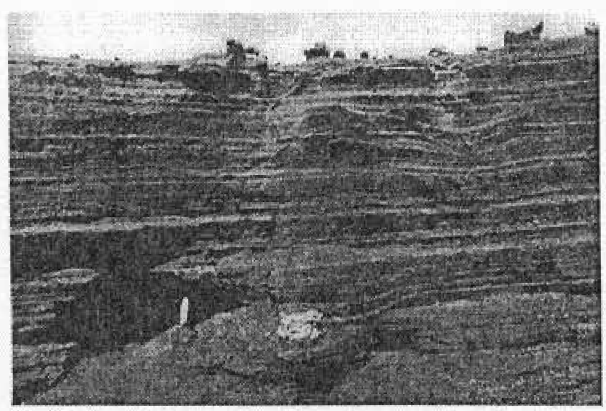


Fig. 29. Proximal deposits of the main cone at the edge of Mesa de los Hornitos (Stop 9). This sequence consists of 2.2 m of alternating ash and lapilli layers. Bomb sags and abundant fragmented bombs can be seen at this section.

vents could be heard from the distance. Beyond the "volcancitos" the zone of "hornitos" followed the course of the lava stream. On March 3, 1944, faint-violet "flames" were observed from the "volcancitos" and "hornitos" and occasionally small incandescent stones were ejected from the vents. Above the large flames arose continuously waving tongues of bluish-white gases. The vents from which the "flames" issued were lined with a thin coating of fused viscous lava. This description suggests very high temperatures at the gas outlets of the "volcancitos" and "hornitos", capable of re-melting the lava.

Walking along the trail towards the main cone, we find a junction of trails; one angles up the cone slope toward the top of the volcano and another goes south to the central part of "Mesa de los Hornitos". We will follow the latter to Stop 10. The surface is rugged and walking will become more difficult.

At "Mesa de los Hornitos" some "volcancitos" (Fig. 30) and "hornitos" can still be seen. In the area of the "volcancitos" several "tumuli", or piles of spatter are present (Fig. 31). Here, we can observe the structure of one of the "volcancitos", which consists of several blocks of black glassy lava coated with a whitish film of carbonates and other sublimates from the fumaroles. Some of the rocks at this vent were emplaced as dikes with an almost N-S trend showing strong striations. Various workers have reported high but decreasing fumarolic temperatures in this area (Global Volcanism Network Bulletin, 1986, 1988, 1989): 473°C in 1985; 375°C in 1986; 336°C in 1988; 305°C in 1989. Around this site we can easily find large bombs up to 2 m in diameter.

Stop 11 (19.491°N, 102.252°W): Parícutin crater.

The crater was visited for the first time on November 3, 1943, by veteran alpinist Arnaldo Pfeiffer. He and Sgt. José Rosales of the Mexican Army made a second ascent on December 4. After the second visit they stated that the area below the low NE rim was very muddy, hot, and steamy. The crater rim was no more than 1 m wide, and they could not see into the depths of the crater because of vapor clouds.

On December 19, 1943, Mr. Abraham Camacho and Mr. Celedonio Gutiérrez (later designated the "resident observer" of the volcano) made an ascent and reported a funnel-shaped crater with steep slopes covered by "small and large rocks" (lapilli and bombs). In the bottom of the crater were three funnel-shaped vents, oriented E-W and issuing vapors. A large fumarole at the eastern wall of the crater emitted abundant vapor and the surrounding walls were encrusted with white and yellow sublimates. At this time the cone was ~300 m high.

Later, on January 5, 1944, Luis Aguilar and Sgt. José Rosales ascended the cone and reported that the crater had the form of a shallow dish and contained five funnel-shaped vents, the principal one near the SW edge of the crater. The odor of hydrochloric acid pervaded the crater, which contained abundant yellow sublimates.

Foshag and González-Reyna first visited the crater on May 25, 1944. They described it as eccentrically funnel-shaped with a very sharp crater rim, the SW wall being steeper than the other slopes and the SW rim lower. The inner slope consisted of loose lapilli and a few bombs, and sloped directly to a small basin 2 to 3 m in diameter. At times, the basin showed incandescent lava and even produced a few weak gas bubbles that spattered some lava about a meter into the air. Usually, however, the basin floor was covered with ash that slid from the nearby slopes. The vent occasionally showed mild and sporadic emissions of brownish ash in a thin tenuous column. Higher than this vent was a circularly depressed area in the side wall of the crater. This saucer-shaped depression was about 8 m in diameter and bounded by an almost continuous circular crack containing two small irregular vents with a halo-like zone of thin sublimates around it. Steam issued continuously from these vents, but the vapor was typically invisible, its presence attested only by the deep roar from the vents and the clouds of

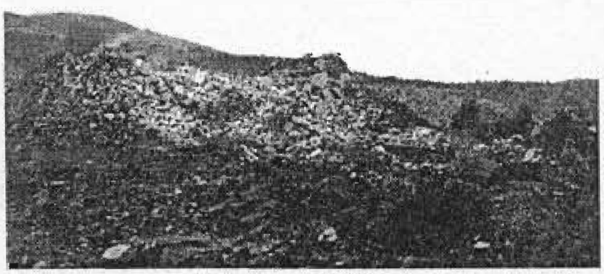


Fig. 30. View of a volcancito at Mesa de los Hornitos (Stop 10). It still has weak low-temperature fumaroles and is surrounded by tumuli and hornitos. The rocks are whitish due to fumarolic sublimates. This photo was taken during the rainy season.

Fig. 31. Detail of a tumulus near the volcancito of Fig. 30 at Mesa de los Hornitos (Stop 10). Tumuli are made of spatter and some still have weak fumaroles during the rainy season.

condensed vapor that rose irregularly above the crater rim. At other times, though, the vapors rushed out of the vents as visible jets of steam, as if escaping from a nozzle at high velocities. No distinct odor was apparent on the crater rim. Foshag and González-Reyna photographed these vents, which showed a different trend (N-S) from that previously described.

On November 26, 1944, Foshag and González-Reyna visited the crater again, describing changes in the intervening 6 months. The rim of the crater was rounded and broad, allowing them to walk easily around it. The highest point was the eastern edge (2,740 m). The crater had two vents. The central vent was a deep narrow funnel with little activity. The south vent was a saucer-shaped depression that contained 5 or 6 orifices. The largest orifice was an irregular opening, perhaps 4 m across, which blew off at frequent intervals, tearing incandescent lava from its throat and carrying bombs well above the crater rim. Other orifices showed violent but erratic steam and ash ejections. The observers felt strong and frequents tremors, which were sometimes followed by an increase in activity at the orifices.

From "Mesa de los Hornitos" there is another trail to the summit of Parícutin. This is a difficult climb because we have to walk over very loose coarse cinders. From the plateau, the crater may be reached in 15 to 30 minutes depending a person's fitness level. Please be aware of the effects of altitude; some people may feel dizziness. The trail takes us to the southern rim of the crater.

From the rim, we will be able to observe the crater and its two funnel-shaped vents, aligned N-S (Fig. 32). The largest and northernmost crater was described as the central vent by Foshag and González-Reyna (1956). The crater rim is a broad place where walking is easy and safe. The bottom of the crater is currently flat, filled by the material that slides down from the slopes of the inner walls. From the rim it is possible to follow a trail to the bottom, but instead, we will follow around to the western rim where, during the rainy season (June-August), a low-temperature fumarole can be observed right beneath the cross. Just behind the cross, on the outer flank of the cone, is a channel through the ashes that leads to the base. Some people may wish to begin their descent at this time; others will continue to the next stop.

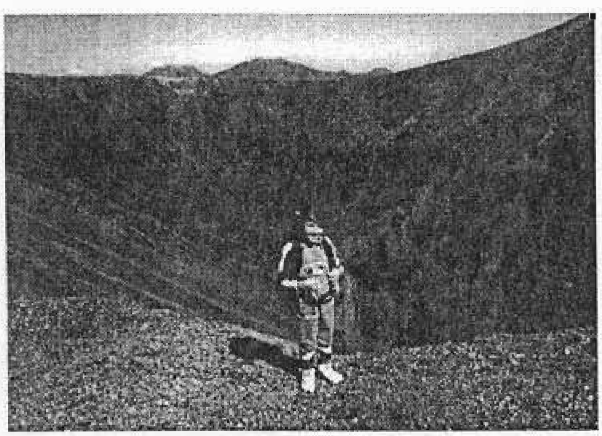


Fig. 32. View toward the N of the Parícutin crater showing its two vents; taken from the southern crater rim (Stop 11).

Stop 12 (19.492°N, 102.247°W): Nuevo Juatita Vent Mound.

During the 9-year eruption of Parícutin Volcano, lava and spatter were commonly emitted from vents at the NE and SW bases of the cone. The main focus of lava emission commonly shifted from one side of the volcano to the other. Two distinct vents were notable on the NE flank. The first, called Sapichu, after the Tarascan word for "small", was born on the night of October 18, 1943, following two days of increasingly intense earth tremors. At 23:00, a series of five or more vents opened suddenly in a NE-trending line about 300 m long. The Sapichu activity began with heavy explosions; bombs were hurled into the air from the new vents to a height greater than the main cone. By October 21, one of the vents had become dominant. It was centered about 720 m from the main cone axis, and built a horseshoe-shaped cone of ejecta that was kept open to the NE by the movement of lava. The continuous eruptions of Sapichu yielded some of the most spectacular sights to be seen during the history of Parícutin. The activity of Sapichu ended on January 8, 1944, its lavas having reached 4 km north of the cone. The Sapichu cone was progressively buried by lava from the SW-flank vents (see Plate 3B in Luhr and Simkin, 1993). The summit of Sapichu cone was finally buried in December 1947.

Three years after the death of the Sapichu vent, lava again began to erupt from the NE flank in January 1947. This vent was later named Nuevo Juatita by Ezequiel Ordóñez, and it became the main lava vent for the last 5 years of the eruption. This long activity built a complex mound of multiple vents, which reached a final altitude of 2,692 m, just 79 m below the NE rim of the main cone, and 117 m below the high point on Parícutin's W rim. Compared to Sapichu, Nuevo Juatita was centered closer to the main cone, just 420 m from its axis.

Following the trail clockwise along the western rim of the main cone we reach the northern rim. From this site we have a nice view of Nuevo Juatita vent mound (Fig. 33) and the valley to the north of the volcano. The summit of Nuevo Juatita is covered with white fumarolic minerals. Fumaroles are still active on the summit of Nuevo Juatita, and can be seen from a distance, especially during the rainy season. It is possible to descend the NE slope of Parícutin cone to reach Nuevo Juatita vent mound, but in the interest of time we will return along the crater rim to the cross and descend the channel on the W

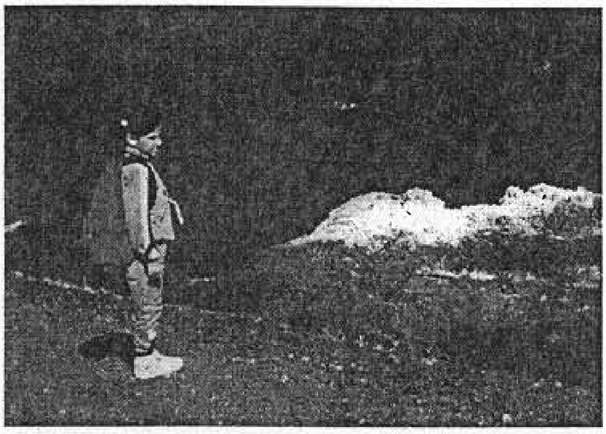


Fig. 33. Nuevo Juatita vent mound, which is covered with whitish fumarolic sublimates. View is toward the NE from the NE rim of Parícutin's crater (Stop 12).

slope. Then we will hike or ride horses back to the vans and proceed to the town of Angahuan.

Stop 13 (19.547°N, 102.225°W): Angahuan.

Prior to the eruption, Angahuan was the third largest town of the region with 1,098 people (the largest was San Juan Parangaricutiro with a population of 1,895) (Nolan, 1979). Angahuan was the most Indian of the nearby villages, where all the population spoke Tarascan and many of them were monolingual. The people of Angahuan generally kept to themselves, and few men had ventured far from the boundaries of the community lands prior to 1943. The rule of endogamy (choosing partners from within the community) was strong, although the village contained a few women married in from other communities. Community lands were not sold to outsiders and people from other places were not allowed to live permanently in Angahuan. It is said that school teachers sent by the government during the 1930s usually did not remain long, largely because of local hostility. Before the volcano, Angahuan restricted its social and economic interactions with other communities to an extent that seems to have been unusual for Sierra Tarascan towns in the early 1940s.

With the eruption of Parícutin volcano, things changed radically for the people of the region. They were the subjects of considerable attention and were exposed to an unprecedented number of people from beyond the region. By February 25, 1943, not only scientists, but tourists, reporters, curiosity seekers, and even peasants from other villages were arriving to witness the spectacle of Parícutin's eruption. Thus, from the very beginning of the physical catastrophe that destroyed their lands, the people affected by Parícutin volcano were also exposed to a radically changed social environment. As refugees, tourist guides, and even field research assistants, they came into contact with a great variety of people from beyond their region, especially North Americans and urban Mexicans. They became subjects of concern and planned social change for officials representing the rapidly modernizing Mexican nation. During the years of the eruption, hardly anyone from Angahuan left the community, although people from Parícutin, San Juan Parangaricutiro, and other affected towns started to leave for new settlements. Very few Angahuan men accepted the opportunity to work as *braceros*, or contract laborers in the U.S. under a formal government program, and almost none took temporary residence elsewhere in Mexico. The people of Angahuan tried to survive guiding tourists and felling the forests, since planting seeds in pure ash was not successful. Angahuan had become dependent economically on tourists who came to see the eruptions.

After the volcano ended its activity in 1952, as word spread that the show was over, the tourist traffic virtually disappeared from the region. Some men were finally forced to leave Angahuan as temporary laborers because the lands were still too unproductive to support a population that had increased slightly during the eruption years. Although a new generation of tourists eventually returned to see the volcano they had read about in school textbooks, Angahuan tourist guides still look wistfully at the conical black form of Parícutin. Most probably feel what one expressed: "It would be nice if the volcano would erupt again - just a little bit" (Nolan, 1979).

Angahuan was the adamantly Indian town, greatly changed, yet clinging to outward expression of tradition, a condition complicated by the interests of tourists and folk-craft developers. Angahuan is the only town among the ones affected by the eruption where almost everyone still speaks Tarascan. Traditional Tarascan dress, particularly for women, is still common in Angahuan and the town still preserves traditional housing even though new styles might be seen. A tourist-guide industry had emerged by 1971. The primary function of the guides seemed to be a combination of allowing a flow of income into the community and ensuring the least possible contact between locals and outsiders. Tourist income primarily benefited hotel keepers and restauranteurs of Uruapan, because Angahuan did not have such facilities. The direct sale of craft items was limited, mediated by the tourist guides, who carefully screened prospective buyers before taking them into homes where wares were displayed. Only in recent times have some shoppers started to display their items on the street, but still this is not a common practice.

Perhaps the most critical issue for the future of Angahuan is the increasing commercialization of visible aspects of the Indian heritage. The importance of the town was based on its proximity to the scene of volcanic devastation and its importance as a staging point for guides and horses. However, by the late 1960s it was being viewed by urban entrepreneurs as a quaint Tarascan village and thus a tourist attraction in its own right.

At this stop in downtown Angahuan we will see the plaza and at one side of the main square, the 16^{th}-century church (Fig. 34). Details about the church can be found in Rodríguez-Elizarrarás et al. (1993). The church was built by franciscan friars about the year 1560 and shows the austerity of Roman-style architecture from northern Europe in the great smooth unadorned façade. The front door, however, shows combinations of Arabic (such as in the rectangles of the arches of the principal door and in the choir window) and Gothic styles (such as in the decoration of the interior of the rectangles (alfiz) with the silhouette of Saint Jacob) (Fig. 35). This church is considered a treasure re-discovered by the time of the eruption of Parícutin.

Stop 14: Angahuan visitors center.

Following the main street beside the square, we continue for 2 km to reach the southern outskirts of the town. There, a visitor's center provides overnight accomodations and a restaurant, both run by the community. Also, a small exhibit about the eruption of Parícutin may be visited. This is the usual starting place for visits to the ruins of San Juan Parangaricutiro and to the cone of Parícutin, whether walking or riding horses that are available for rent. On a clear day, the view from the balcony of the restaurant is spectacular, embracing the lava fields, the cone of Parícutin, Nuevo Juatita vent mound, and the older Equijuata and Capatzún volcanoes surrounded by the San Juan lavas (Stop 3). On clear days, but especially early in the morning or at dusk, Volcán de Colima, the most active Mexican volcano, can be seen from here 180 km to the west.

From this site we will return to Uruapan airport for our return flight to Puerto Vallarta.

PETROLOGY AND GEOCHEMISTRY OF THE VOLCANIC ROCKS

The volcanic fields discussed in this guidebook (Mascota, Los Volcanes, Colima, and southern Michoacán-Guanajuato) lie along the volcanic front of the western Trans-Mexican Volcanic Belt, as best a volcanic front can be defined in this tectonically complex setting (see chain of diamonds on Fig. 1). In each of these volcanic-front fields, typical *hy*- and *q*-normative subduction-related suites of calc-alkaline volcanic rocks coexist with *ne*-normative lamprophyres. Representative analyses of these two suites from each of the volcanic fields are listed in Table 1. A large set of volcanic rock analyses is shown in Fig. 36 on a plot of SiO_2 versus K_2O. The calc-alkaline rocks (all open symbols and some closed symbols for Mascota and Los Volcanes) fall along a common trend of positive slope at the base of this diagram. This trend is typical of those found for subduction-related volcanic arcs and is thought to arise through the combined action of fractional crystallization and crustal contamination. The contemporaneous lamprophyric rocks range to much higher K_2O values at a given silica content, and phlogopite crystallized from many of them. The silica-rich lamprophyric magmas were probably similarly derived from more primitive lamprophyres through fractional crystallization and crustal contamination. But what is the relationship between the calc-alkaline and lamprophyric magmas and why have they repeatedly erupted at the same time and place along the front of the western Trans-Mexican Volcanic Belt?

Primitive members of these two suites have quite distinct major element compositions, normative mineralogies, modal mineralogies, oxygen fugacities, trace element abundances, and B/Be values. Nonetheless,

Fig. 34. The 16^{th}-century church of Angahuan (Stop 13) has woodwork with a combination of Arabic- and Gothic-style carvings.

Fig. 35. Detail of the wood carving at the main door on the Angahuan church (Stop 13), showing the Gothic image of Saint Jacob.

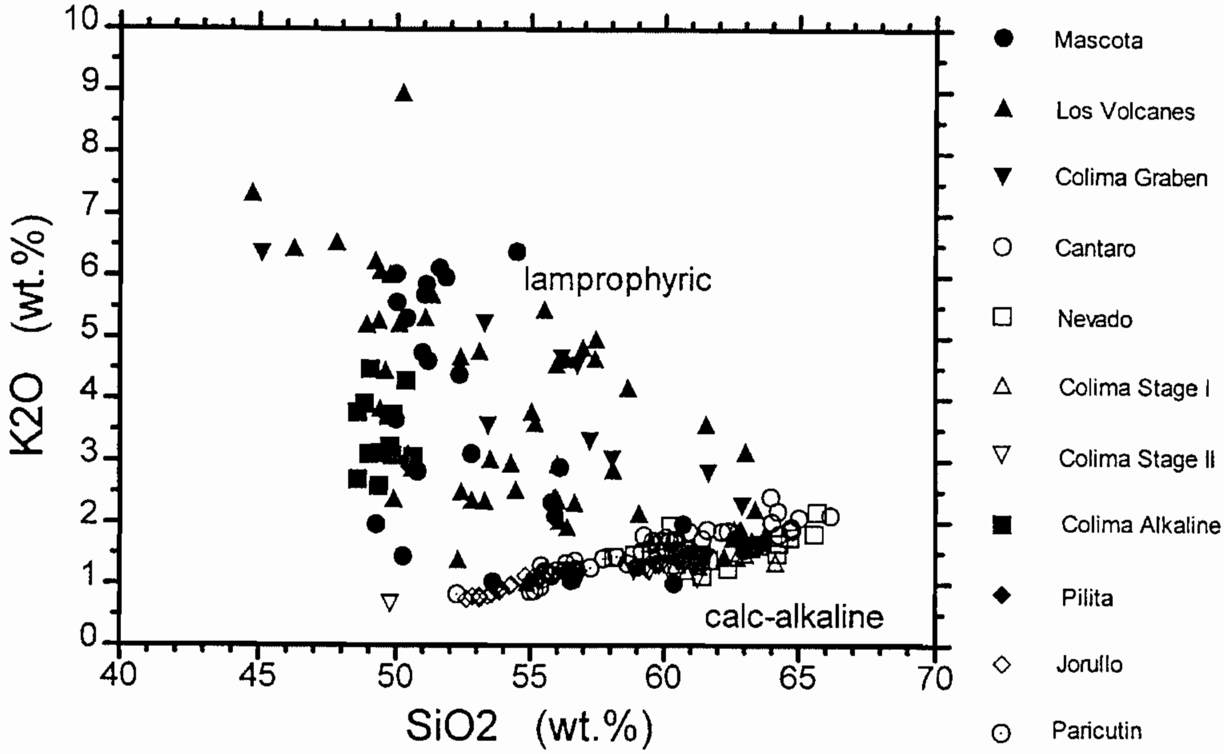


Fig. 36. Plot of SiO_2 versus K_2O showing 247 whole-rock compositions from the western Trans-Mexican Volcanic Belt. All data were normalized to 100% anydrous with Fe^{3+} = 20% Fe^{total}. Data sources: Mascota (Carmichael et al., 1996), Los Volcanes (Wallace and Carmichael, 1989, 1992), Colima Graben (Allan and Carmichael, 1984), Cantaro (Luhr and Carmichael, 1990b), Nevado (Robin et al., 1984, 1987), Colima Stage I (Luhr, 1993), Colima Stage II (Luhr and Carmichael, 1980, 1982, 1990a; Robin et al., 1984, 1987), Colima alkaline (Luhr and Carmichael, 1981), Pilita and Jorullo (Luhr and Carmichael, 1985), Paricutin (Wilcox, 1954; McBirney et al., 1987).

they are similar in their relative trace element abundances as shown by the morphology of patterns on multi-element plots, and they have overlapping Sr, Nd, and Pb isotopic ratios. These observations are consistent with origins for both suites from a common source region in which veins of phlogopite-apatite-garnet pyroxenite cross-cut mantle peridotite (Luhr et al. 1989; Wallace & Carmichael 1989 and 1992; Carmichael et al. 1996; Hochstaedter et al. 1996; Luhr, 1997), the primitive lamprophyres are envisioned to result mainly from melting of the veins. With increasing wall-rock contribution, the vein melt component is diluted toward typical calc-alkaline basalt compositions. These still retain the isotopic and trace-element signatures of the vein component, although they are considerably diluted in element abundances. In this sense, the lamprophyres of the western Mexican Volcanic Belt represent the geochemical "essence" of subduction-zone magmatism. Following the terminology of the Basaltic Volcanism Study Project (1981), the western Mexican Volcanic Belt lamprophyres are viewed as "probes" of phlogopite-pyroxenite veins in the mantle wedge above the subducted Rivera and Cocos slabs.

If lamprophyres are the geochemical "essence" of subduction-zone magmatism, why aren't they more commonly reported in active arcs? Similar phlogopite-pyroxenite veins may form above most subducted slabs, but the nearly pure lamprophyric vein melts may rarely erupt to the surface. More likely, these low-volume hydrous melts lose heat and water during ascent, crystallizing and stagnating in the crust to form lamprophyric dikes. As reviewed by Rock (1991), calc-alkaline lamprophyres, of which minettes are the most common variety, are usually emplaced in convergent margins settings as dikes intruding calc-alkaline granitoids. Rock (1991) cited composite intrusions and other field and geochronologic evidence indicating that lamprophyric and granitic magmas were commonly coeval, as also demonstrated for the volcanic equivalents (lamprophyres and calc-alkaline magmas) of the western Mexican Volcanic Belt.

The unusual extensional tectonic setting of the western Mexican Volcanic Belt has apparently allowed a diverse set of such lamprophyres to rise to the surface and erupt. Other examples of young lamprophyres erupted in active subduction-related arcs can also be cited, although the role of extensional tectonics is not generally so clear for these. The best analog is probably the 12.4-0.5 Ma trachybasalts reported by Hausback (1984) from the southern end of Baja California, which erupted at a similar stage in the rifting history of Baja as proposed by Luhr et al. (1985) and Allan et al. (1991) for rifting of the Jalisco Block. Other equivalents are present in the Tabir-Feni arc of Papua New Guinea, where partial melts from the subduction-modified mantle wedge have risen along extensional faults that transect the remnant New Ireland forearc (McInnes & Cameron 1994; Herzig et al. 1996).

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Table 1

Representative analyses of volcanic rocks from the western Trans-Mexican Volcanic Belt

Eruption Date							
Location	Mascota		Los Volcanes		Colima Graben		Colima
Rock Type	MIN	BA	MIN	HA	PKA	HKA	MIN
Sample	Mas-4A	Mas-21	158	229	B116	M163A	SAY-7E
			Major Elements (wt.%)				
SiO_2	49.27	53.27	49.29	60.80	40.78	60.45	48.20
TiO_2	1.75	0.82	2.27	0.69	3.54	0.65	1.64
Al_2O_3	12.70	16.78	12.20	18.30	9.15	16.83	11.62
Fe_2O_3	5.45	2.28	5.52	3.07	11.22	3.55	4.22
FeO	2.48	4.45	1.31	1.32	3.19	1.16	3.27
MnO	0.14	0.12	0.10	0.07	0.18	0.08	0.11
MgO	9.52	8.08	5.49	2.38	8.28	2.69	11.81
CaO	7.66	8.44	9.88	5.58	6.67	5.15	8.32
Na_2O	2.89	4.09	2.40	4.30	2.05	4.76	3.28
K_2O	5.17	1.01	4.39	1.39	5.73	2.73	3.58
P_2O_5	1.28	0.28	1.80	0.11	0.75	0.37	1.32
LOI	0.98	0.57	3.78		7.83	1.13	1.96
Total	99.29	100.19	98.43	98.01	99.37	99.55	99.33
			CIPW Norms (wt.%)				
q				13.73		7.76	
or	31.20	5.97	27.54	8.39	18.51	16.43	21.81
ab	11.00	34.78	21.58	37.23		41.04	14.74
an	6.56	24.57	10.13	27.11		16.82	6.59
lc					14.77		
ne	7.56				9.05		7.51
di	18.92	12.58	23.54	0.41	25.25	5.52	21.49
hy		8.38	1.07	10.17		8.88	
ol	15.89	9.41	5.00		17.32		19.16
ac					2.12		
mt	2.44	2.10	2.15	1.35	3.66	1.44	2.35
il	3.40	1.56	4.58	1.35	7.41	1.25	3.21
ap	3.04	0.65	4.43	0.25	1.92	0.88	3.15

Rock Type: MIN, minette; BA, basaltic andesite; HA, hornblende andesite; PKA, phlogopite-kalsilite ankaratrite.

Major elements and some trace elements (V, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba) were determined by X-ray fluorescence analysis. Pb concentrations were determined by isotope dilution. The remaining trace elements were determined by instrumental neutron activation analysis. These data are from: Luhr and Carmichael (1980, 1981); Allan and Carmichael (1984); Luhr and Carmichael (1985); Wallace and Carmichael (1989, 1992); McBirney et al. (1987). CIPW norms were calculated from major element analyses assuming $Fe^{3+} = 15\% Fe^{total}$ and after normalization to 100% anhydrous.

B and Be analyses are from Hochstaedter et al. (1996). Isotopic data are from Heatherington (1988), Luhr (1997), and Housh (unpublished).

Table 1 (Cont.)

Eruption Date							
Location	Mascota		Los Volcanes		Colima Graben		Colima
Rock Type	MIN	BA	MIN	HA	PKA	HKA	MIN
Sample	Mas-4A	Mas-21	158	229	B116	M163A	SAY-7E
Trace Elements (ppm)							
Sc	22.30	24.20	21.3	10.4	17.30	10.4	26.70
V	239	243		82	307	89	265
Cr	356	277	144	8.4	145	34	691
Co	35.40	31.90	26.1		54.80	15.6	
Ni	250	150	90	20	122	25	436
Cu	95	56		30	242	36	90
Zn	113	54		58	423	77	80
Rb	54	11	51	9	45	35	73
Sr	2674	898	5109	1489	3280	1400	3079
Y	25	15		15	15	17	29
Zr	506	113	491	129	307	194	554
Nb	18		25		33	15	16
Cs	0.5	0.4	1.84	<0.5	<0.6	1.1	1.0
Ba	2749	417	3510	550	3120	1160	4230
La	52.6	14.1	124	18.1	84.0	33.0	82.3
Ce	122	30.6	284	35	180	68	188
Nd	63	16	131	16	59	32	93
Sm	10.80	3.64	19.80	3.14	6.52	4.86	15.24
Eu	2.94	1.13	4.85	0.98	1.60	1.45	4.50
Tb	0.86	0.45	1.10	0.50	0.49	0.49	1.20
Dy	4.10	2.28	4.83		2.30	2.50	5.50
Yb	1.72	1.42	1.33	0.93	0.89	1.11	1.74
Lu	0.19	0.15	0.17	0.12	0.13	0.18	0.18
Hf	16.4	2.5	13.7	3.5	8.7	4.7	17.9
Ta	0.53	0.17	1.10		1.99	0.40	
Pb	24.6	5.5					40.0
Th	5.27	1.08	11.50	2.60	3.51	4.95	7.13
U	1.89	0.43	3.80	0.70	1.38	1.55	2.41
B	2.3	4.1					10.6
Be	6.12	1.00					5.65
Isotopes							
$^{87}Sr/^{86}Sr$							0.70388
Epsilon Nd							2.8
$^{206}Pb/^{204}Pb$							18.64
$^{207}Pb/^{204}Pb$							15.56
$^{208}Pb/^{204}Pb$							38.37

Table 1 (Cont.)

Eruption Date	1869		1759	1774?	1943	1952
Location	Colima	Pilita	Jorullo	Jorullo	Paricutin	Paricutin
Rock Type	A	HTB	BA	BA	BA	A
Sample	Col-2	Jor-46	Jor-44	Jor-11	51-W-18	FP-16-52
			Major Elements (wt.%)			
SiO_2	60.84	49.21	52.10	54.18	54.59	60.07
TiO_2	0.62	1.33	0.81	0.92	0.99	0.81
Al_2O_3	17.80	14.19	16.44	18.74	17.83	17.28
Fe_2O_3	2.16	4.54	1.56	2.47	2.01	1.37
FeO	3.10	3.75	6.05	4.31	5.43	4.39
MnO	0.11	0.12	0.14	0.11	0.12	0.10
MgO	2.74	8.32	9.29	4.64	5.44	3.73
CaO	5.88	7.68	8.46	7.87	7.25	6.16
Na_2O	4.76	4.59	3.47	4.52	3.95	4.00
K_2O	1.46	2.82	0.74	1.11	0.91	1.67
P_2O_5	0.22	1.37	0.14	0.24	0.27	0.28
LOI	0.14	1.19	0.44	0.36	0.20	0.08
Total	99.83	99.11	99.64	99.47	98.99	99.94
			CIPW Norms (wt.%)			
q	10.00				2.98	10.63
or	8.69	17.08	4.43	6.62	5.44	9.87
ab	40.45	24.48	29.62	38.67	33.85	33.93
an	22.96	10.02	27.29	27.83	28.61	24.30
lc						
ne		8.28				
di	4.00	15.99	11.34	8.18	4.91	3.66
hy	10.56		14.30	12.69	19.32	13.63
ol		15.73	8.73	1.57		
ac						
mt	1.64	2.58	2.42	2.13	2.36	1.81
il	1.18	2.58	1.56	1.77	1.90	1.54
ap	0.51	3.24	0.32	0.56	0.63	0.65

Table 1 (Cont.)

Eruption Date	1869		1759	1774?	1943	1952
Location	Colima	Pilita	Jorullo	Jorullo	Parícutin	Parícutin
Rock Type	A	HTB	BA	BA	BA	A
Sample	Col-2	Jor-46	Jor-44	Jor-11	51-W-18	FP-16-52
			Trace Elements (ppm)			
Sc	12.00	18.11	25.20	19.11	17.30	13.76
V	169	217	186	216		
Cr	34	338	564	75	145	76
Co		41.9	38.6	25.0	35.0	18.1
Ni	32	248	261	44	116	63
Cu	21	72	60	35	168	34
Zn	63	172	61	66	140	72
Rb	22	17	10	16	14	27
Sr	625	2250	397	615	607	541
Y	15	18	20	21		
Zr	152	203	100	130	116	173
Nb						
Cs	0.7	0.8	0.39	0.39		0.66
Ba	494	1222	218	355	315	604
La	12.7	91.5	7.3	12.6	13.1	19.6
Ce	28.3	172.0	17.4	29.4	29.6	40.9
Nd	15	67	11	17	21	25
Sm	2.97	7.79	2.78	3.39	3.8	4.3
Eu	0.99	2.04	0.86	1.12	1.32	1.29
Tb	0.42	0.62	0.50	0.48	0.67	0.64
Dy	2.90	2.68		2.94		
Yb	1.69	1.25	1.58	1.70	1.79	1.78
Lu	0.15	0.17	0.231	0.22	0.28	0.28
Hf	3.5	5.6	2.35	3.5	2.94	3.84
Ta		0.960	0.137	0.240	0.38	0.49
Pb	4.5	15.3		5.2		
Th	1.84	5.19	0.59	1.14	0.94	1.91
U	0.74	1.18	0.28	0.39		
B	7.5	5.2	2.8			17.3
Be	1.12	3.21	0.64			1.35
				Isotopes		
$^{87}Sr/^{86}Sr$	0.70355	0.70443	0.70405	0.70404	0.703927	0.70412
Epsilon Nd	5.4	2.0	3.6	4.0	3.8	2.5
$^{206}Pb/^{204}Pb$	18.58	18.70	18.62	18.65	18.64	18.69
$^{207}Pb/^{204}Pb$	15.55	15.60	15.57	15.62	15.58	15.60
$^{208}Pb/^{204}Pb$	38.29	38.52	38.34	38.38	38.36	38.47