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A PRELIMINARY REPORT ON THE COMENDITIC DOME AND ASH FLOW COMPLEX OF SIERRA LA PRIMAVERA, JALISCO

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RESUMEN

El complejo volcánico La Primavera, del Pleistoceno superior, que constituye la Sierra La Primavera al poniente de Guadalajara, consiste de lavas comendíticas (riolítico-peralcalinas), derrames piroclásticos, pómez, y de depósitos lacustres y fluviales asociados. Los domos y derrames, que se formaron a lo largo de dos zonas arqueadas están divididos en dos unidades cartografiables en base de su forma topográfica y su contenido de fenocristales. Estas dos unidades, la porfídica y la afírica, se distinguen también por sus características químicas de elementos traza y edades de K-Ar.

Las lavas más antiguas contienen 5-15 por ciento de fenocristales (sanidino sódico $\geq$ cuarzo $\gg$ ferrohedenbergita $>$ fayalita $>$ ilmenita), y se caracterizan por una peralcalinidad mayor que las lavas afíricas más recientes. La erupción de las lavas más antiguas comenzó hace 100,000 años, aproximadamente, a lo largo de una zona de fractura con dirección hacia el norte, formando domos con diámetro de 1 a 4 km. La erupción de las últimas lavas porfídicas se efectuó hace 60-80.000 años aproximadamente. Estas muestran pequeños cambios en la composición de sus fenocristales y se caracterizan por la concentración de sus elementos, tanto de mayores como de traza, que es intermedia entre aquella de las unidades porfídicas más antiguas y la de la mayoría de las unidades afíricas.

Las primeras lavas del grupo afírico son semejantes en su composición a las últimas del grupo porfídico. La mayor parte de las unidades afíricas tuvieron su erupción hace 50-60,000 años, a lo largo de una zona de fractura con dirección hacia el sur, y fluyeron radialmente desde el centro del complejo, como derrames en forma de lengüeta, 3-4 km de largo. La más reciente de las unidades afíricas es un domo de 2 km de diámetro, con unos 30,000 años de edad, que acusa una tendencia hacia la disminución de la peralcalinidad con el tiempo.

La tendencia química de los productos volcánicos del complejo La Primavera parecen reflejar la evolución geoquímica de la parte superior de una cámara magmática debajo de la Sierra La Primavera.

El área dentro de los dos anillos de domos contiene una secuencia compleja de derrames piroclásticos, pómez, y depósitos lacustres y fluviales. La Toba Tala, un derrame piroclástico afírico sin piroconsolidación, aflora en esta región central y en una gran extensión de las cuencas que circundan la Sierra La Primavera. En vista de que la toba se acuña en contra de los derrames afíricos, aquella no puede ser más antigua que 60,000 años; sin embargo, la evidencia topográfica sugiere que puede ser tan reciente como 5-10.000 años. Tres fallas normales, cuyos bloques hundidos están al poniente, cortan las rocas volcánicas de La Primavera, y todas tienen manifestaciones de aguas y vapores termales.

Las inclinaciones radiales leves de las superficies planares de depósito de las capas lacustres, la presencia de estas capas en la parte alta de la secuencia y muy por encima del nivel de las cuencas circundantes, la erupción de lava a lo largo de zonas arqueadas que sugieren fracturas anulares incipientes y el flujo radial de los derrames afíricos, todo sugiere que la Sierra La Primavera sufrió intumescencia durante el emplazamiento gradual y crecimiento de una cámara magmática somera. La naturaleza reciente de la actividad volcánica, la evidencia abundante a favor de la presencia de una cámara magmática de unos 14 km de diámetro, la circulación de grandes volúmenes de aguas calentadas y la proximidad de la gran área metropolitana de Guadalajara califican la Sierra La Primavera como una meta de primera importancia para el desarrollo de energía geotérmica y para la observación continua de los riesgos volcánicos.

ABSTRACT

The late Pleistocene La Primavera volcanic complex, which makes up the Sierra La Primavera, west of Guadalajara, consists of comenditic (peralkaline-rhyolitic) lavas, ash flows, air-fall pumice, and associated lacustrine and fluvial deposits. The domes and flows, which were erupted along two arcuate zones, are divided into two map units on the basis of topographic form and phenocryst content. These two groups, the porphyritic and the aphyric, are also distinct with respect to major and trace element chemistry and K-Ar ages.

The oldest lavas contain 5-15% phenocrysts (sodic sanidine $\geq$ quartz $\gg$ ferrohedenbergite $>$ fayalite $>$ ilmenite), and are characterized by greater peralkalinity than the younger aphyric units. They began to erupt approximately 100.000 years ago along the northerly fracture zone, forming domes 1-4 km in diameter. The last porphyritic lavas were erupted aproximately 60-80.000 years ago. They show minor changes in the composition of the phenocrysts and are characterized by major and trace element concentrations intermediate between those of the older porphyritic units and most of the aphyric units.

The first lavas of the aphyric group are similar in composition to the last of the porphyritic group. Most of the aphyric units were erupted approximately 50-60.000 years ago along the southerly fracture zone and flowed radially away from the center of the

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complex, forming 3-4 km long coulees. The youngest of the aphyric group is a 2 km diameter dome about 30.000 years old that continues the trend toward decreasing peralkalinity with time.

Chemical trends in the volcanic products of La Primavera complex seem to reflect the geochemical evolution of the upper portion of a magma chamber beneath the Sierra La Primavera.

The area within the two rings of domes contains a complicated sequence of ash flows, air-fall pumice, and lacustrine and fluvial deposits. The Tala Tuff, an aphyric nonwelded ash flow, is exposed in this central region and over a large area in the basins surrounding the Sierra La Primavera. Because the tuff laps against aphyric flows, it can be no older than approximately 60.000 years; however, topographic evidence suggests that it may be as young as 5-10,000 years. Three normal faults, down to the west, cut La Primavera volcanic rocks and all have associated hot spring or steam vent activity.

Shallow radial dips on planar depositional surfaces and lake beds, the position of the lake beds high in the section and well above the level of the surrounding basins, the eruption of lava along arcuate zones suggestive of incipient ring fractures, and the radial flow directions of the aphyric couless all suggest that the Sierra La Primavera has undergone intumescence during the gradual emplacement and growth of a shallow-level magma chamber. The recency of the volcanic activity, the abundant evidence for the presence of an approximately 14 km diameter magma chamber, the circulation of large volumes of heated water, and proximity to the large metropolitan area of Guadalajara should make the Sierra La Primavera a prime target for both development of geothermal energy and the monitoring of volcanic hazards.

INTRODUCTION

The mechanisms that produce high-silica magmas within large, shallow-level magma chambers, whether such magmas erupt as rhyolites or crystallize at depth to form granitic plutons, are poorly understood. Studies of caldera-forming ash flow eruptions (Williams, 1942; Lipman *et al.*, 1966; Smith and Bailey, 1966; Hildreth, 1977 Christiansen, in preparation) have been invaluable in characterizing the thermal and chemical gradients within silicic magma chambers just prior to great eruptions, and there is a growing body of data which suggests that crystal fractionation and partial melting are not adequate mechanisms to explain the chemical zonation in ash flows (Shaw *et al.*, 1976; Hildreth, 1976, 1977). Study of rhyolite dome complexes, especially if consideration is given to temporal variation in the chemistry of eruptive units, may provide additional perspectives on the differentiation mechanisms that operate within shallow-level silicic magma chambers.

The main purpose of this research is, therefore, to trace the chemical evolution of a rhyolitic complex through time, interpreting it as the periodic sampling of an evolving magma chamber at depth. La Primavera complex, immediately west of Guadalajara, Jalisco, Mexico, is ideally suited for such a study because (1) it is volumetrically large with vents located along posible incipient ring fracture zones that suggest the horizontal limits of the proposed magma chamber, (2) it is well-exposed and contains fresh, glassy rocks necessary for detailed chemical studies, and (3) it spans a time period which, while short enough to assure it is all one magmatic episode, is long enough to permit resolution of the eruptive sequence by K-Ar dating. This paper is only a progress report; a more complete story awaits completion of field work and additional chemical analyses.

REGIONAL GEOLOGY

The Sierra La Primavera and surrounding lowlands east to Guadalajara and west to Tala (Figure 1) are the topographic expression of late Pleistocene volcanism which produced a complex of comenditic domes, coulees, air-fall pumice, and ash flows. La Primavera complex lies at the intersection of the two major Cenozoic volcanic provinces of Mexico. Its peralkaline rocks stand in marked chemical contrast to both the andesitic stratovolcanoes and basaltic cinder cones that make up the bulk of the Trans-Mexican Volcanic Belt, and to the metaluminous silicic lavas and ash flows that dominate the Sierra Madre Occidental (Gunn and Mooser, 1970; de Cserna, 1961).

The Sierra Madre Occidental is cut by large north-south normal faults that end or are covered by younger volcanic rocks near the Río Grande de Santiago. Here, at the southern end of the province, the silicic ash flows and lavas are intercalated with basalts and basaltic andesites of the Trans-Mexican Volcanic Belt, and to the west and southwest of Presa de La Vega, they thin sufficiently to expose Cenozoic intrusive rocks, Paleozoic metamorphic rocks, and Cretaceous limestones (López-Ramos and Hernández-Sánchez Mejorada, 1968). The western portion of the Trans-Mexican Volcanic Belt trends northwest-southeast and contains the Pleistocene and Recent andesitic stratovolcanoes of Ceboruco, Tequila, and Colima. Volcán de Colima stands in an anomalous position, south of the western portion of the Trans-Mexican Volcanic Belt, and within a large north-south graben. A line of 10 basaltic andesite cones trends southeast from the Sierra La Primavera toward Lago de Chapala (Figure 1). The southernmost cone is offset by one of innumerable east-west normal faults. This normal faulting has broken the area into a series of grabens, one of the largest being occupied by Lago de Chapala. Southeast of Lago de Chapala, the trend of the Trans-Mexican Volcanic Belt becomes nearly east-west and the number of andesitic and basaltic cones increases dramatically.

Much of the area now occupied by La Primavera complex appears to be underlain by older andesitic and basaltic lavas, which are locally exposed in canyons within the complex, at its margins, and are common as accidental débris in air-fall pumice deposits. Unfortunately, nothing is known of the prevolcanic basement underlying the

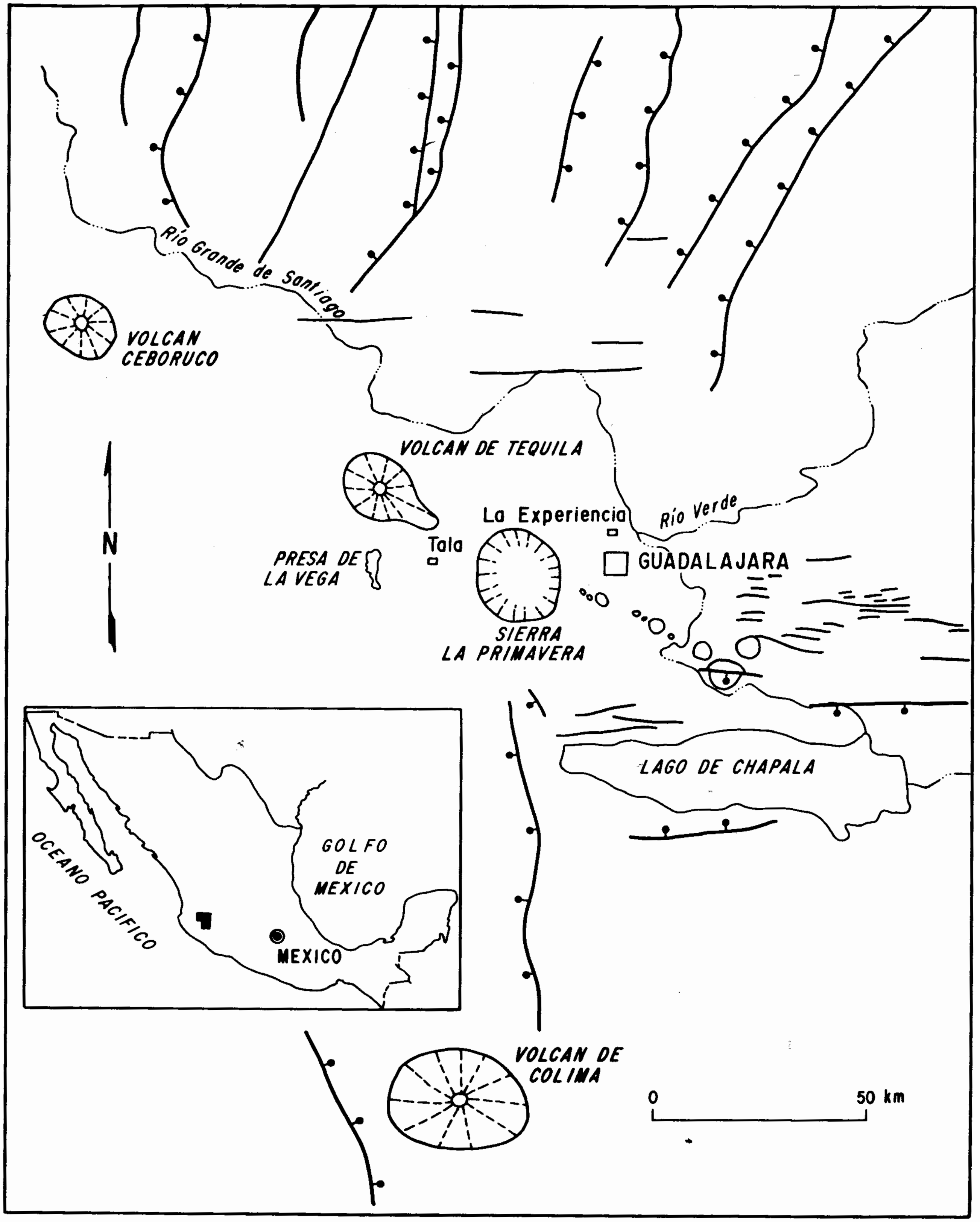

Figure 1.—Map showing the location of the Guadalajara region in Mexico and of Sierra La Primavera within the western part of the Trans-Mexican Volcanic Belt. Circles indicate major and minor volcanoes, whereas lines the major faults and lineaments.

Sierra La Primavera.

South of La Primavera complex, there are eroded remmants of andesitic to rhyolitic flows. Reconnaissance mapping to the north and northeast (C. M. Gilbert, personal communication, 1977) has revealed a sequence of phenocryst-rich, dacitic to rhyolitic ash flows and lavas, approximately 2 to 4 m.y. old, unconformably overlying still older Cenozoic silicic volcanic rocks. Represented as phenocrysts in all of these rocks are plagioclase, biotite, and hornblende, phases never seen in La Primavera volcanic suite. The peralkaline, phenocryst-poor magmas of La Primavera complex appear to have been erupted after a gap of nearly two million years in silicic volcanic activity.

The intersection near Guadalajara of the east-west normal faults of the Trans-Mexican Volcanic Belt with the north-south faults of the Sierra Madre Occidental and the Colima graben may, in some way, be responsible for localization of silicic volcanism in the Sierra La Primavera.

ERUPTIVE UNITS

The lavas of La Primavera complex have been divided into two map units based on phenocryst content, an aphyric and a porphyritic group. Since it is not possible to subdivide the two groups in the field, further distinctions are based on chemistry and/or K-Ar dating. The Tala Tuff, an unwelded ash flow, is the other major map unit. The area within the ring of porphyritic domes, here referred to as the central region, consists of various pyroclastic deposits. Work in this region is incomplete; therefore, no attempt has been made to show the complicated relations on the sketch map (Figure 2). Future field work will be focused on this complex portion of the Sierra La Primavera.

Porphyritic units.—The porphyritic units consist of 15 domes, 1-4 km in diameter and 100-300 m in height. The total volume of exposed porphyritic units is approximately 10 km^3. Erosion of the domes has proceeded far enough that they are no longer steep-sided, and, locally, columnar-jointed interior portions are exposed. Most outcrops of these units, however, consist of pumiceous carapace, a small proportion of which is devitrified. Unvesiculated black glass is common, and in many exposures is quite friable because of its finely perlitic texture. The vents for these domes delineate 360° of a circle, 12 km in diameter, whose center lies within the central region, west of Mesa El Nejahuate. Within this circle is another arcuate zone of vents, including those of Mesa El Nejahuete, Cerro Alto, and Cerro Chato, which intersects the main circle at Mesa El Burro (Figure 2). This distribution of vents is almost certainly controlled by fracture zones, here interpreted as the results of regional intumescence produced by the gradual emplacement and growth of a magma chamber.

The proportion of phenocrysts varies in different domes, ranging from 5% to 15% by volume. Sodic sanidine and quartz, the former generally more abundant, together comprise approximately 97-99% of the phenocrysts, the remainder being ferrohedenbergite, fayalite, and ilmenite, roughly in the proportions 25:5:1. None of the phenocrysts are systematically zoned, neither optically nor on the basis of microprobe analyses, and the range in composition of a phase within a sample is extremely small. All phenocrysts contain glass inclusions.

Sodic sanidine occurs as clear, simply-twinned, tabular grains, from 0.5 to 2.5 mm in length. In thin section, the quartz phenocrysts are rounded or slightly embayed hexagons, 0.3-1.5 mm in diameter, and commonly contain fluid inclusions. By far the most abundant ferromagnesian phase is ferrohedenbergite. It occurs as slightly pleochroic, green to brownishgreen, prismatic grains, 0.7-1.2 mm long. Fayalite occurs as small, round, honey-colored grains, few larger than 0.2 mm in diameter, and are commonly rimmed by opaque alteration products. Homogeneous ilmenite is commonly found as tiny, rounded inclusions in ferrohedenbergite and fayalite, and ocassionally as small, separate phenocrysts 0.2 mm in diameter. Zircon, apatite, and chevkinite (?) have been found in the porphyritic unit of Cerro El Pedernal and in the dome of Mesa El Leon, which contains rare, oxidized-exsolved titanomagnetite as well.

Aphyric units.—The eight aphyric units differ morphologically from the porphyritic units; their steep sides are well-preserved, and most units form coulees approximately 100 m thick and 3-4 km long, rather than domes. The Llano Grande coulee, Cerro El Colli, and La Culebra dome appear to represent single continuous extrusions of 0.5 and 0.2 km^3 of magma, respectively. Cerro El Tajo, Cerro Las Planillas, and Cerro San Miguel, on the other hand, are made up of several coulees, each consisting of 0.3-0.5 km^3 of magma, erupted from a single central vent area. The aphyric units of Cerro El Pedernal and Cañon de Las Flores were erupted from mixed centers, *i. e.*, centers from which both porphyritic and aphyric units were discharged. The total volume of exposed aphyric lavas is approximately 10 km^3, thus equalling the porphyritic units in volume. Vents for these units define an arcuate zone delineating 250° of a 14 km diameter circle whose center is displaced south of that for the porphyritic units. This circle is also interpreted as a structurally-controlled ring fracture zone.

Pumiceous carapace forms the surface of nearly all the aphyric lavas, presumably because erosion has not proceeded far enough to strip it away. Obsidian lenses are common near flow margins and are generally dense, black and lacking megaphenocrysts, with sparse feldspar and pyroxene microlites in thin section. In some outcrops, the obsidian shows a slightly resinous luster indicative of hydration. Small spherulites are not uncommon in the dense glass, occuring usually in bands. Totally devitrified glass in the aphyric units is exposed only where faulting or blasting has revealed interior portions of the flows.

Tala Tuff.—The name Tala Tuff is applied to the aphyric ash flow that forms the slope between the Sierra La Primavera and the town of Tala, and is exposed in the central region of the Sierra, in

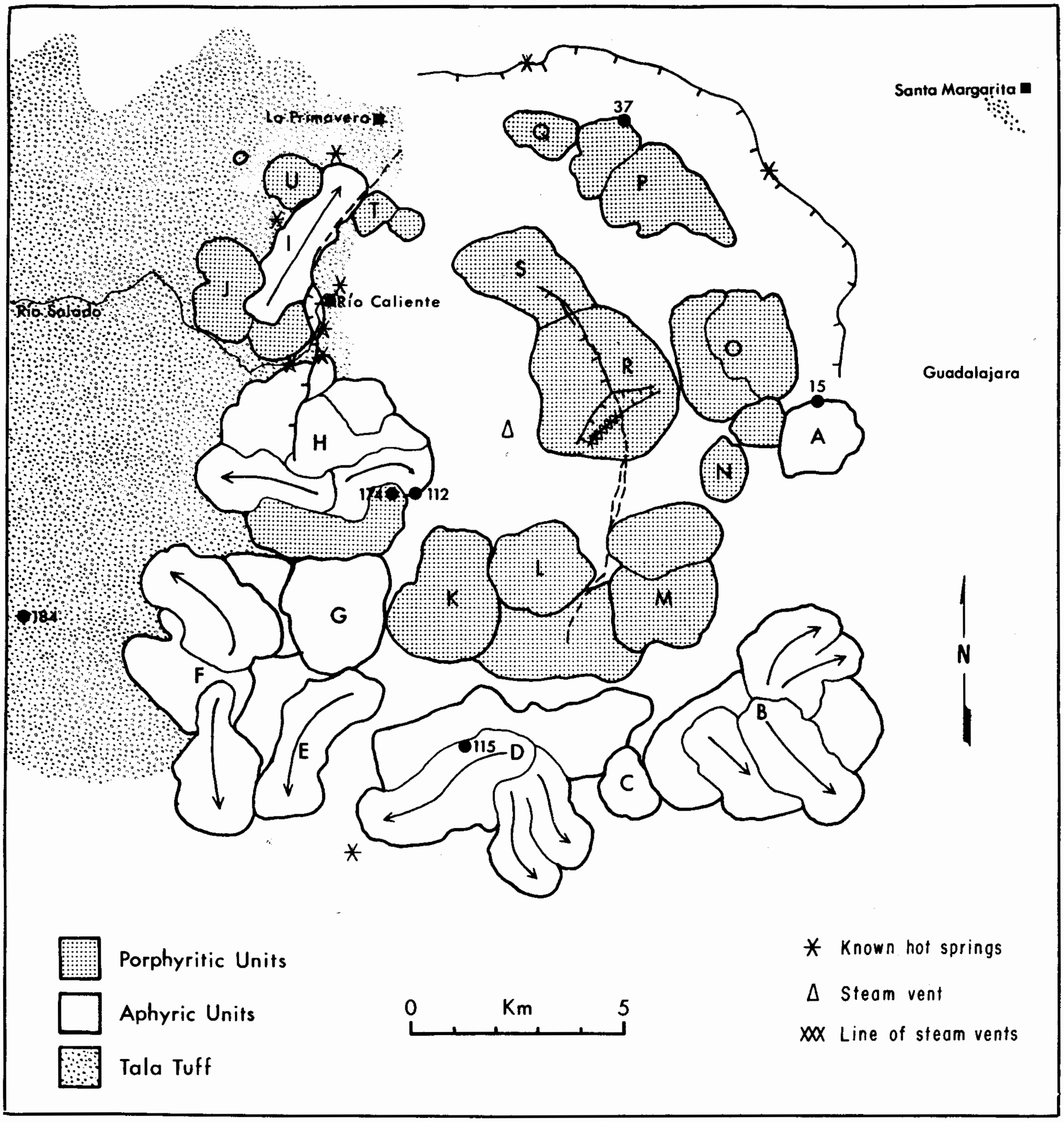

Figure 2.—Sketch map of La Primavera complex.—Faults are shown with solid lines where there is a topographic scarp. Dots next to numbers are sample localities referred to in the text. The following is a list of the domes, flows, and centers referred to in the text: (A) El Colli; (B) Cerro El Tajo; (C) La Culebra; (D) Cerro Las Planillas; (E) Llano Grande; (F) Cerro San Miguel; (G) La Puerta; (H) Cerro El Pedernal; (I) Cañón de Las Flores; (J) Mesa El León; (K) Cerro El Culebreado; (L) Cerro El Tule; (M) La Cuesta; (N) Las Pilas; O) Cerro El Chapulín; (P) Mesa La Lobera; (Q) Pinar de La Venta; (R) Mesa El Nejahuete: (S) Cerro Alto; (T) Cerro Chato; (U) Mesa El Burro.

spotty outcrops east of the village of La Primavera, and near Santa Margarita (Figure 2). The tuff consists of at least two flow units, separated locally by lenses of cobble-sized fluvial débris; in most outcrops, however, this break as not detected. Nowhere are the outflow sheets of the tuff welded. In exposures in the fault scarp near Río Caliente (Figure 2), the tuff is sintered, locally altered by vapor-phase action, or more rarely, partially welded.

The Tala Tuff reaches its maximum exposed thickness in a canyon just east of Tala, where it is 70 m thick, though the base is unexposed. The present estimate of the minimum volume of magma erupted in the outflow sheets (assuming a density of 1 gm/cm^3 for the ash flow deposit and 2.3 gm/cm^3 for the unvesiculated magma) is approximately 8 km^3. The exact source is not known, but the spatial distribution of the tuff indicates that it probably lies within the central region of La Primavera complex.

AGE RELATIONS OF THE ERUPTIVE UNITS

Several lines of evidence are used to establish the eruptive sequence in La Primavera complex: topographic expression, overlapping field relations, tephrostratigraphy and K-Ar dating. The oldest units appear to be the porphyritic domes. The porphyritic units have retained less of their original steep-sided topography than the aphyric units. Aphyric pumice is found in all surficial air-fall pumice deposits. The only porphyritic pumice yet found outside the central region, is in a quarry at La Experiencia (Figure 1), where it rests on a 0.7 m soil horizon developed on the top of a 3.5 m.y. old (Table 1) ignimbrite, and is overlain by interbedded aphyric pumice and soil. In the mixed centers, the aphyric flows overlap and cut through the porphyritic units.

Preliminary K-Ar dates on sanidine and glass of 10 of the units (Table 1) suggest that most of the porphyritic lavas were erupted 80-100,000 years ago; a second group of porphyritic lavas, including those of Mesa El Leon, Cerro El Pedernal, Cerro El Culebreado, and La Cuesta, were erupted perhaps 60-80,000 years ago; most of the aphyric flows are about 50-60,000 years old, and aphyric Cerro El Colli is approximately 30,000 years old. While single K-Ar dates of such young ages must be viewed with some skepticism, they are compatible with the relative ages arrived at from geological considerations. The author hopes to refine the dating of the eruptive sequence with replicate K-Ar dates and perhaps C^{14} age determinations on charcoal within air-fall pumice sequences.

The age of the Tala Tuff is not known. The tuff is banked against the aphyric flows of Cerro El Pedernal and Cañón de Las Flores, proving it can be no older than approximately 60,000 years. In a number of places, however, the sloping surface of the tuff is still preserved. Despite the unwelded nature of the deposit, it has not been reduced to a rolling topography. Fumarolic pipes and conduits are wellpreserved and strikingly displayed east of Tala. In the 1912 ash flow in the Valley of Ten Thousand Smokes, Alaska (which is similar in volume, thickness, and welding characteristics to the Tala Tuff), such fumaroles are rooted in the top 10-15 m of the ash flow (E. W. Hildreth, personal communication, 1976). This suggests that there has been little erosion of the Tala Tuff. It may be quite young, perhaps 5-10,000 years old.

CENTRAL REGION OF THE SIERRA LA PRIMAVERA

Accumulated within the ring of porphyritic domes and surrounding Mesa El Nejahuate and Cerro Alto are various pyroclastic, fluvial, and lacustrine deposits, not shown on the sketch map (Figure 2). These deposits form an extensive planar surface whose average elevation of 1,800 m is about 300 m below the crests of Mesa El Nejahuete and Cerro El Tule. West of Mesa El Nejahuete, the surface slopes gently north-northwest, away from Cerro El Tule; east and north of Mesa El Nejahuete, the surface is more steeply inclined and dips radially away from the Mesa. Steep-walled arroyos cut in this surface expose ash flows, air-fall pumice, pumice breccias, talus breccias, lake beds and reworked pumice with an aggregate thickness of as much as 150 m. Ashy lake beds are common and one 5 m thick bed, dipping 2° east, is continuously exposed over several square kilometers between Cerro El Chapulin and Mesa La Lobera.

Two ash flows, in addition to the Tala Tuff, are exposed in the central region. The older of the two consists of both aphyric, light-colored pumice and dark-colored pumice containing sparse feldspar and quartz phenocrysts, as well as pumice lumps that represent a mixture of the two magmas. Refractive indices of the glasses suggest the magmas are rhyolitic and rhyodacitic in composition. This mixed magma ash flow is overlain unconformably by an ash flow somewhat similar in composition and appearance to the Tala Tuff, but containing 0.7%

Table 1.—Potassium-argon age determinations.

Sample Number	Location	Material Dated	K_2O wt. %	Radiogenic ^{40}Ar moles/g x 10^{-18}	Radiogenic Ar wt. %	Apparent Age m. y.
15	C. El Colli	Glass	4.44	1.42	3.0	.029 ± .008
115	C. Las Planillas	Glass	4.40	3.91	11.6	.062 ± .008
106	C. San Miguel	Glass	4.39	3.86	7.9	.052 ± .007
25	La Cuesta	Sanidine	6.14	6.23	6.0	0.70 ± .011
174	C. El Pedernal	Sanidine	7.29	7.63	15.9	.073 ± .004
148	M. El Nejahuete	Sanidine	6.51	7.69	4.5	.082 ± .016
133	C. El Tule	Sanidine	6.26	8.59	13.1	.095 ± .008
14	Pinar de La Venta	Sanidine	6.89	9.43	14.8	.095 ± .008
37	M. La Lobera	Sanidine	6.31	7.68	14.0	.079 ± .008
89	M. El Burro	Sanidine	6.41	8.92	26.0	.097 ± .006
65-4	La Experiencia	Sanidine	5.84	290.7	77.8	3.45 ± 0.10

Age error (1σ) is calculated, with slight modification, following Dalrymple and Lanphere (1969).

phenocrysts of quartz and feldspar. Along the Río Salado, at the northern end of Cerro El Pedernal (Figure 2), the mixed magma ash flow is overlain by the Tala Tuff. The relationship between the two younger ash flows, however, is not known, and it is possible that the porphyritic ash flow is simply the slightly more mafic portion of a compositionally-zoned Tala Tuff.

FAULTING

Three major fault systems are related to La Primavera complex; all are nearly vertical normal faults, down to the west. The first system can be traced for approximately 8 km from near the village of La Primavera to Cerro El Pedernal (Figure 2). Displacement on this fault is maximum near Río Caliente and decreases both north and south. At Río Caliente, the Tala Tuff and overlying pyroclastic and lacustrine deposits are cut by a 100 m scarp; at the northern end of Cerro El Pedernal, 30 m of the scarp is an over-steepened slope, devoid of vegetation. Large hot springs that discharge along this fault are the source of the Río Salado. The fresh appearance of the scarp in the aphyric lavas of Cerro El Pedernal and in the unwelded Tala Tuff suggests that the faulting is young.

The second fault system runs in a gentle arc, concave to the west, extending 9 km from Cerro Alto to south of Cerro El Tule. On the upper surfaces of Cerro Alto and Mesa El Nejahuete, its expression is a 5-10 m scarp; on the southern slope of Mesa El Nejahuete, the trace of the fault is marked by a ridge of pumiceous porphyritic lava. It appears that faulting and eruption may have been closely related, for the same fault which offsets Mesa El Nejahuete seems to have provided structural control for the extrusion of lava on its flanks. Perpendicular to the trace of this arcuate fault is a small graben, 2 km long and 0.5 km, wide, which down-drops the south shoulder of Mesa El Nejahuete a maximum of 40 m. Dozens of steam vents emanate from the southeast bounding fault of the graben and the flow rock there is strongly opalized. Altered ground on the northwest bounding fault marks the location of numerous, formerly active fumaroles. This steam vent activity probably represents boiling from the same deep water table which, 350 m lower at Río Caliente, nearly intersects the ground surface and gives rise to voluminous hot springs along the fault scarp.

The third and most puzzling of the fault systems is that traced by an irregular scarp in a 13 km arc from Cerro El Colli to the village of La Primavera. This 10-20 m scarp in aphyric air-fall pumice and alluvium forms the northeast boundary of a closed depression between it and the porphyritic domes of Cerro El Chapulin, Mesa La Lobera, and Pinar de La Venta. Two warm spings emerge along the base of the scarp. The fault and adjacent closed depression may represent partial collapse of the roof zone of a magma chamber in response to a decrease in magmatic pressure in that sector; alternatively, the fault may be antithetic to northeastward tilting accompanying intumescence of the aphyric dome complex. This faulting must be quite recent; a scarp in such unconsolidated material would not last long.

WHOLE ROCK CHEMISTRY

All units in La Primavera complex are high-silica comendites[1]. Whole rock wet chemical analyses and CIPW norms of samples representative of the various groups of eruptive units are given in Table 2. Table 3 contains a partial list of trace element abundances; for some elements the analyses are still in progress. Consistent with the mildly peralkaline nature of these rocks are the relatively low abundances of Ca, Mg, Sr, and Ba and their enrichment in Na, Fe, Zr, Hf, Ta, and rare earth elements (REE) relative to calc-alkalic rhyolites. While all the units are similar in gross composition, there are systematic differences that appear to be related to their ages.

Chemically, the porphyritic units are separable into two groups, the division being the same as that suggested by K-Ar dating. The porphyritic units which are thought to have erupted 80-100,000 years ago are higher in FeO, MnO, TiO_2, Zr, Hf, and light REE, lower in Rb, Cs, and U, and are less siliceous[2] than those which appear to have erupted 60-80,000 years ago. To the older group belong Cerro El Tule, Las Pilas, Cerro El Chapulin, Mesa La Lobera (Sample No. 37 in Tables 2 and 3), Pinar de La Venta, Mesa El Nejahuete, Cerro Alto, Cerro Chato and Mesa El Burro. The younger group consists of Cerro El Culebreado, La Cuesta, and those units from mixed centers, Cerro El Pedernal (Sample No. 174) and Mesa El Leon. The aphyric lavas of Cerro El Pedernal (Sample No. 112) and Cañon de Las Flores, which were erupted from mixed centers, as well as La Puerta, have major and trace element compositions similar to the younger porphyritic lavas.

The aphyric lavas of Cerro El Tajo, La Culebra, Cerro Las Planillas, Llano Grande, and Cerro San Miguel are all similar to one another in composition, and are represented in Tables 2 and 3 by the youngest flow from Cerro Las Planillas (Sample No. 115). Erupted approximately 50-600,000 years ago, they are slightly less peralkaline, even poorer in FeO, MnO, TiO_2, Zr, Hf, and light REE, and richer in SiO_2, Rb, and Cs than the younger group of porphyritic lavas. Cerro El Colli (Sample No. 15), erupted about 30,000 years ago, is the least peralkaline, richest in SiO_2, Rb, Sc, and U, and poorest in FeO, MnO, TiO_2, MgO, Zn, Y, Nb, Zr, Hf, and light REE of all the lavas.

Chondrite-normalized whole rock REE patterns are given in Figure 3A illustrating a progressive depletion in light REE and increase in the size of the negative Eu anomaly with time in the lavas. The patterns for the low temperature, 77% SiO_2 portion of the Bishop Tuff, a compositionally-zoned ash flow with calc-alkalic affinities (Hildreth, 1977), for an Icelandic comendite with only 75.5% SiO_2, but mafic phenocrysts virtually identical in compo-

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[1] The term comendite here refers to a quartz-normative, peralkaline lava with less than 12.5% normative femic minerals. Peralkalinity is in turn defined as the molecular proportion of Al_2O_3 being less than that of Na_2O and K_2O combined, and its measure, the agpaitic index, is the ratio $(Na_2O + K_2O)/Al_2O_3$.

[2] Because of the varying degree of hydration of the samples depending on whether they are dense glass or pumice, comparison of major elements must be made using the analyses recalculated water-free and normalized to 100%.

Table 2.—Representative whole rock wet chemical mayor element analyses *.

GROUP:	Older Porphyritic	Younger Porphyritic	Mixed Center Aphyric	Aphyric	Aphyric	Tala Tuff
SAMPLE No.:	37	174	112	115	15	184
SiO_2	75.34	75.08	76.47	76.81	76.67	74.94
TiO_2	0.17	0.12	0.12	0.09	0.06	0.09
Al_2O_3	11.53	11.09	11.42	11.66	11.83	11.33
Fe_2O_3	0.87	0.88	0.80	0.69	0.56	1.10
FeO	1.25	0.88	1.00	0.80	0.67	0.65
MnO	0.07	0.05	0.06	0.04	0.04	0.05
MgO	0.04	0.04	0.05	0.04	0.02	0.03
CaO	0.28	0.19	0.22	0.23	0.31	0.17
Na_2O	4.59	4.32	4.68	4.71	4.63	4.55
K_2O	4.70	4.67	4.54	4.50	4.43	4.57
P_2O_5	0.006	0.004	0.006	0.006	0.006	0.005
H_2O+	0.94	2.48	0.70	0.50	0.88	3.05
H_2O	0.16	0.19	0.10	0.09	0.22	0.33
Total	99.95	99.99	100.17	100.17	100.33	100.86
CIPW Norms calculated water-free and normalized to 100%:						
Q	29.83	31.93	31.29	31.12	30.91	30.82
Or	28.24	28.57	27.15	26.83	26.45	27.86
Ab	35.81	34.13	35.92	37.38	38.88	35.92
Ac	2.47	2.53	2.27	1.93	1.57	3.17
Na-ms	0.91	0.87	1.13	0.86	0.38	0.69
Ilm	0.24	0.17	0.17	0.13	0.08	0.13
Di	1.09	0.74	0.85	0.89	1.20	0.65
Hy	1.40	1.06	1.22	0.85	0.49	0.75
Ap	0.01	0.01	0.01	0.01	0.01	0.01
Differentiation Index:	93.88	94.63	94.35	95.33	96.26	94.60
Agpaitic Index:	1.10	1.10	1.10	1.08	1.05	1.10

* Analyses were performed by the autor using classical wet chemical techniques (Carmichael, 1970), except for Na_2O and K_2O which were analyzed by J Hampel using flame photometry. All oxides were analyzed at least in duplicate and precision is as follows: SiO_2, Na_2O, K_2O ± .1 wt. %; Al_2O_3 ± .05 wt. %; Fe_2O_3, FeO ± .02 wt. %; CaO ± .01 wt. %; TiO_2, MnO ± .005 wt. %; P_2O_5 ± .001 wt.%. H_2O was analyzed by loss on ignition and seems to give incorrectly high values (perhaps due to loss of Na on heating) which lead to high totals.

sition to those in La Primavera lavas (Carmichael, 1967), and for a more highly peralkaline pantellerite from New Zealand (Nicholls and Carmichael, 1969) are plotted in Figure 3B. La Primavera magmas resemble the Bishop Tuff in the large negative Eu anomaly, and the peralkaline lavas in the high concentration of REE.

The Tala Tuff is quite distinct from La Primavera lavas in trace element concentrations, despite being similar to the younger porphyritic units in major element composition. Relative to the lavas, the tuff is enriched in the heavy REE, Rb, Cs, Th, U, Hf, Ta, and Zn, has concentrations similar to those of the lavas for the light REE, Mo, and Sb, and is depleted only in Sc.

PHENOCRYST CHEMISTRY

The range in composition of the phenocrysts among the various porphyritic units is remarkably small. For this reason, only the electron microprobe analyses of the phenocrysts from two samples representative of the two groups of porphyritic lavas are shown in Table 4. None of the phenocrysts is systematically zoned.

Of all the phenocrysts, the sodic sanidine shows the most variation between the two groups of porphyritic units, the younger and older groups containing 57.2% and 54.5% of the albite molecule, respectively. The anorthite component is less than 1% in both groups and the difference between them is not considered significant.

In general, mafic phenocrysts are more abundant in the older group than in the younger group of porphyritic units. The olivine and clinopyroxene of both groups are extremely iron-rich; MgO is well under 1% in both phases. The ferrohedenbergite of the younger group of lavas has slightly lower MgO and MnO and higher Na_2O and CaO than the presumably older lavas. No systematic differences have been resolved between the fayalites of the two groups of porphyritic units due to uncertainties in the microprobe analyses of these slightly oxidized olivines.

The ilmenites of the two porphyritic groups are similar; molecular percentage of R_2O_3 ranges from 3.8 to 5.4. The composition of the ilmenite is the same whether it is an inclusion in ferrohedenbergite or fayalite, or is present as a separate

Table 3.—Representative whole rock trace element analyses (PPM).

GROUP:	Older Porphyritic	Younger Porphyritic	Mixed Center Aphyric	Aphyric	Aphyric	Tala Tuff
SAMPLE No.:	*37*	*174*	*112*	*115*	*15*	*184*
La	82 ± 2	56 ± 2	—	40 ± 1	38 ± 1	40 ± 1
Ce	169 ± 3	119 ± 2	—	91 ± 2	82 ± 2	89 ± 3
Nd	68 ± 3	54 ± 3	—	40 ± 2	32 ± 2	54 ± 4
Sm	11.44 ± .05	10.11 ± .04	—	8.40 ± .04	7.88 ± .03	12.72 ± .05
Eu	.13 ± .02	.09 ± .01	—	.07 ± .01	.04 ± .01	.12 ± .03
Tb	1.46 ± .05	1.53 ± .05	—	1.37 ± .04	1.23 ± .1	2.50 ± .08
Yb	6.0 ± .1	6.3 ± .1	—	5.8 ± .1		10.5 ± .2
Lu	.77 ± .08	.94 ± .09	—	.79 ± .08	.75 ± .06	1.37 ± .12
Sum of 8 REE	339.1	247.7	—	187.6	167.0	209.7
Rb	140 ± 7	158 ± 7	—	159 ± 7	176 ± 7	257 ± 11
Cs	2.8 ± .1	3.2 ± .1	—	3.6 ± .1	4.4 ± .2	6.2 ± .2
Th	17.5 ± .1	18.2 ± .1	—	17.2 ± .1	19.6 ± .1	
U	4.82 ± .09	5.50 ± .09	—	5.40 ± .09	6.45 ± .09	9.18 ± .14
Sc	1.04 ± .02	.69 ± .01	—	.72 ± .01	1.08 ± .02	.40 ± .02
Hf	15.1 ± .4	14.2 ± .3	—	11.2 ± .3	8.8 ± .2	19.4 ± .6
Ta	3.33 ± .02	3.63 ± .02	—	3.56 ± .02	3.39 ± .02	6.46 ± .03
Mo	13 ± 4	8 ± 3	—	10 ± 3	8 ± 2	14 ± 4
Sb	.52 ± .08	.43 ± .07	—	.40 ± .07	.68 ± .09	.72 ± .09
Zn	128 ± 5	124 ± 5	—	118 ± 5	89 ± 4	174 ± 6
Nb	45	60	50	55	35	—
Zr	665	560	560	385	240	—
Y	60	60	60	60	50	—
Sr	<10	<10	<10	<10	10	—

Below detection level of NAA: Ba, Au, Ag, Cd, Ni, Cr, As.

[*] Nb, Zr, Y, and Sr were analyzed by the author by XRF against USGS standard G-2; estimated precisión is ± 5 ppm. All other elements were analyzed by NAA (Perlman and Asaro, 1969); stated precision is one standard deviation.

phenocryst. A coexisting titanomagnetite has been found only in a sample from Mesa El Leon, and it was oxidized-exsolved. The zircon, apatite, and chevkinite (?) found in the samples from Mesa El Leon and Cerro El Pedernal have not yet been analyzed.

GEOCHEMISTRY

Magmas which make up large volume, continental, silicic volcanic complexes are generally considered to be products of crustal melting.[*] A melt-fraction produced at depth may (1) begin to rise through the crust but cool and crystallize at depth, or (2) it may rise all the way through the crust and immediately erupt at the surface, or (3) it may coalesce with other melt fractions at depth or intermediate levels to form a magma chamber. which then rises to shallow levels, or (4) it may rise through the crust to be intercepted at shallow levels by a magma chamber. Once incorporated into a magma chamber, the melt may differentiate and react with its wall rocks. Thus the magma that eventually rises from the top of the chamber to erupt at the surface may be quite different chemically from the diapirs that replenish the magma chamber from below. Shallow-level differentiation leaves a mark on the lava which, although difficult to decipher, will distinguish it from a melt that rose directly from source to surface without residing in a magma chamber.

The similarity in bulk composition, phenocryst chemistry and abundances, and eruptive volume (except for the Tala Tuff) of La Primavera units suggests that they all came from a single magma chamber. If each flow represented a separate melting event, one woud expect a greater range in composition, phenocryst assemblage, and size of individual eruptive units, depending on the temperature, volatile content, compositional inhomogeneities, and extent of melting at the source. Even if one assumes that the source was homogeneous and the physical conditions accompanying melting were nearly constant, incremental partial melting would not produce the trends observed in La Primavera magmas. Under these conditions, the first partial melt produced would be enriched in SiO_2 and depleted in FeO, MgO, and TiO_2 relative to subsequent melt-fractions. The reverse is observed in La Primavera lavas; the first magmas to erupt are the least siliceous and richest in mafic constituents.

It is also unlikely that La Primavera units represent tapping of a static zoned magma chamber. Studies of large volume ash flow eruptions from zoned magma chambers (Byers *et al.*, 1976; Lipman *et al.*, 1966; Smith and Bailey, 1966; Hildreth, 1977) have shown that magma at the top of a chamber is more differentiated and poorer in phenocrysts than at deeper levels. Since the collapse of the Long Valley caldera, California, with the eruption of

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[*] An origin for La Primavera magmas involving crystal fractionation of a basaltic liquid cannot be ruled out; however, it is considered unlikely. The volume of parental basaltic liquid necessary to produce at least 30 km³ of 77% SiO_2 magma would be immense. More important is the total lac of less siliceous differentiates, such as comenditic trachyte.

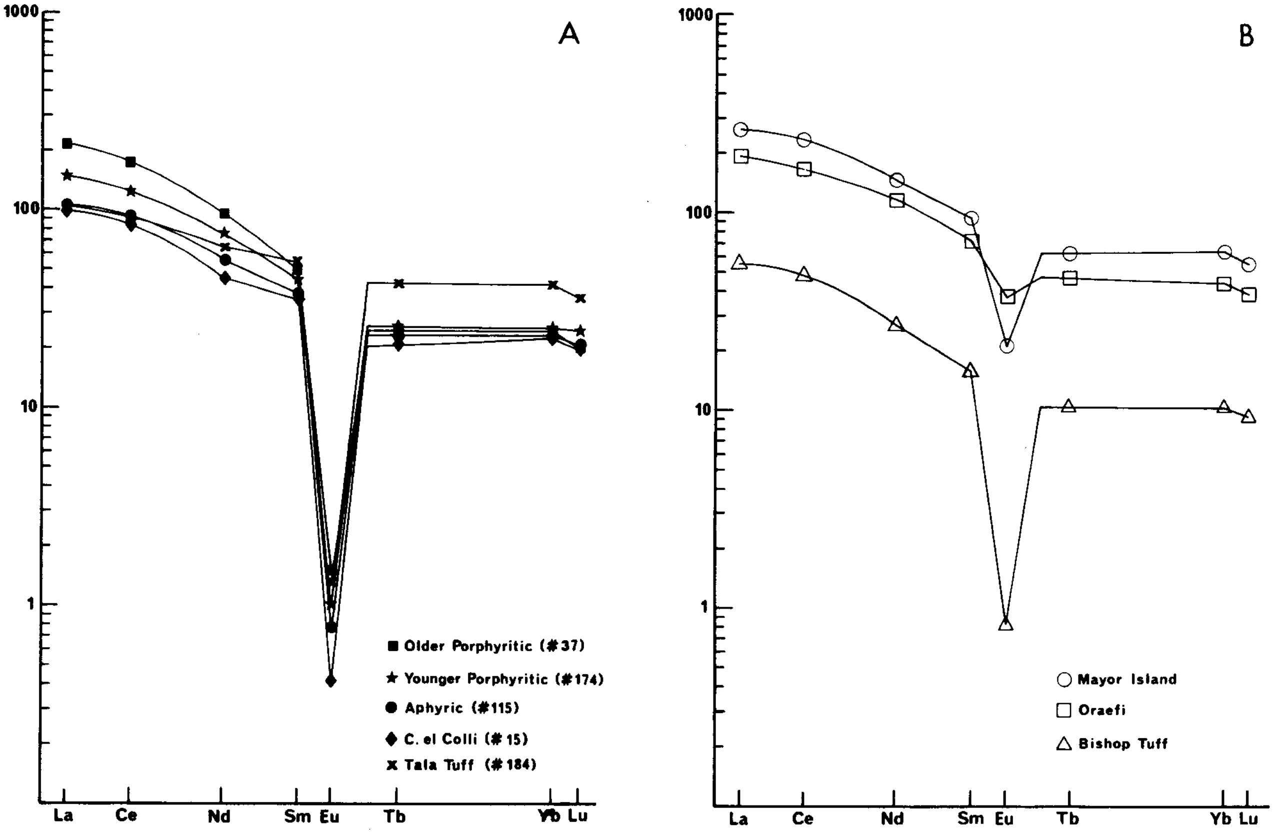

Figure 3.—Chondrite-normalized whole rock REE paterns.—Ordinates are (concentration in sample)/(concentration in Leedey chondrite) (Masuda *et al.*, 1973). (A) Plot of the Tala Tuff and lavas representative of La Primavera complex, showing progressive depletion in light REE with time in the lavas and the divergent trend of the ash flow. (B) Plot of silicic rocks of varying peralkalinity for comparison with La Primavera magmas. The Mayor Island, New Zealand, pantellerite lava contains 74.3% SiO_2 and has an agpaitic index $(Na_2O + K_2O)/Al_2O_3$) of 1.42. The Oraefi, Iceland, comendite contains only 71.5% SiO_2, but has fayalite and ferrohedenbergite phenocrysts virtually identical in composition to those of La Primavera lavas. It has an agpaitic index of 1.02. The sample of the Bishop Tuff is from the highly differentiated, low temperature material erupted 0.7 m.y. ago from the top of the magma chamber beneath Long Valley, California. It is a 77% SiO_2, calc-alkalic rhyolite with an agpaitic index of 0.90. Bishop Tuff data are from Hildreth (1977). Whole rock analyses of the Mayor Island and Oraefi specimens are from Nicholls and Carmichael (1968) and Carmichael (1967), respectively. REE concentration in these two specimens are from this study.

the Bishop Tuff 0.7 m.y. ago, a succession of increasingly mafic and phenocryst-rich lavas have erupted from the same area. Bailey and others (1976) interpret this trend as the tapping of successively deeper levels of the Long Valley magma chamber as the outer portions cool and solidify. La Primavera trend is contrary to these examples; the last lavas are phenocryst-free and are the most siliceous.

Accepting, for the moment, the premise that there is a magma chamber beneath the Sierra La Primavera, it does not appear possible to derive the younger aphyric lavas from the older porphyritic lavas by crystal fractionation of the observed phenocrysts. Sodic sanidine and quartz, due to their large size and proportion among the phenocrysts, would be the most likely phases to separate and, therefore, to control the fractionation trends. Once a melt is peralkaline, fractionation of sanidine would lead to an increasing degree of peralkalinity; however, the opposite is observed. Clinopyroxene makes up less than 0.5% of the older porphyritic units, but by reason of its size, it is the mafic mineral most likely to be fractionated. Neutron activation analysis of the ferrohedenbergite shows it to be enriched in all the REE relative to the whole rock, with a Ce/Yb ratio of 6. Fractionation of ferrohedenbergite from the older porphyritic magmas, which have a Ce/Yb ratio of 28, would result in an increase in this ratio with time, but this ratio actually decreases in the aphyric units, dropping to 15 in Cerro El Colli. The effect of fayalite or ilmenite fractionation cannot be assessed due to lack of trace element data; however, their small size and low abundance[*] would seem to preclude their having as large a role in determining the chemical trends as sanidine and clinopyroxene.

The compositional variation of La Primavera magmas has a coherent pattern in both time and space, and the changes are in directions not likely to reflect and origin involving incremental partial melting, tapping of a static magma chamber, or

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[*] At best the lavas contain no more than 0.09% fayalite and 0.02% ilmenite by volume.

Table 4.—Representative electron microprobe analyses of phenocrysts.

MINERAL	SODIC SANIDINE		FERROHEDENBERGITE		FAYALITE		ILMENITE	
SAMPLE No.:	*37*	*174*	*37*	*174*	*37*	*174*	*37*	*174*
SiO_2	66.63	66.41	48.13	47.96	30.04	30.62	0.45	0.30
TiO_2	—	—	0.33	0.24	0.02	0.02	48.85	48.86
Al_2O_3	19.25	18.96	0.22	0.21	0.00	0.04	0.08	0.06
Fe as FeO	0.20	0.23	30.06	30.02	64.96	64.92	47.10	47.30
MnO	—	—	1.51	1.35	3.55	3.79	1.46	1.33
MgO	—	—	0.62	0.40	0.33	0.20	0.05	0.04
ZnO	—	—	—	—	0.11	0.16	0.10	0.07
CaO	0.12	0.04	18.47	18.68	0.30	0.23	0.06	0.07
Na_2O	6.72	6.45	0.52	0.66	0.00	0.00	—	—
K_2O	7.09	7.69	—	—	—	—	—	—
Total	100.01	99.91	99.86	99.52	99.31	99.98	98.15	98.03

Feldspar components recalculated to 100%:

Ab	57.2	54.5
Or	42.2	45.3
An	0.6	0.2

Clinopyroxene formula units, $X_{1\ p}\ Y_{1\ p}\ Z_2\ O_6$:

Si	Z	1.995	1.996
Al		0.005	0.004
Ca		0.821	0.833
Fe		1.042	1.045
Mn		0.053	0.048
Mg	X, Y	0.038	0.025
Na		0.042	0.053
Al		0.006	0.006
Ti		0.010	0.007
Total:	Z	2.000	2.000
	XY	2.012	2.017

Olivine components recalculated to 100%:

Fa	93.8	93.8
Fo	0.6	0.3
Tp	5.2	5.5
La	0.5	0.4

Calculated ilmenite analyses following Carmichael (1967):

Fe_2O_3	4.86	5.12
FeO	42.73	42.69
Mol. % R_2O_3	4.80	5.00

crystal fractionation*. As this is a report on work in progress, it would be premature to speculate on the derivation of La Primavera magmas. Nevertheless, it appears that the chemical sequence is most readily explained as the occasional sampling of the differentiated top of a magma chamber evolving chemically through time. The task remaining is to discover the processes operating within this magma chamber to produce the changes observed in successive eruptive units. In this regard, it is interesting to note that the Tala Tuff is enriched relative to the lavas in the elements which do not show systematic change with time in the lavas (Lu, Yb, Ta, and Th), as well as those that do (light REE, Rb, Cs, and U). This suggests that the nature of the differentiation process is different when the system produces an ash flow rather than a lava. Perhaps accumulation of the volatile components necessary to produce an ash flow is linked to enriching the magma in trace elements.

PHYSICAL EVIDENCE FOR THE PRESENCE OF A MAGMA CHAMBER

Using the Valles caldera, New Mexico, as a model, Smith and Bailey (1968) enumerated the sequence of events that produces resurgent cauldrons. They described the first stage as consisting of regional intumescence accompanied by the formation of an incipient ring fracture zone, along which small volumes of magma may "leak" to the surface. To quote them,

> "This first stage is partially conjectural, but follows from a logical consideration of the entire Valles sequence and from analogy with other areas."

Little is known about the nature of faulting and deformation during regional intumescence in the well-studied cauldron complexes, because much of the evidence either collapsed with the cauldron block or was buried by ash flows. (For the same reasons, the precursory volcanic activity has been little studied, and the geochemical processes leading to large volume silicic ash flow eruptions are poorly understood). There is no established "type locality" for the intumescent stage of Smith and Bailey's cauldron cycle against which La Primavera complex can be compared. Thus any physical evidence presented here for doming and the presence of a shallow-level magma chamber beneath the Sierra La Primavera will be, of neccessity, circumstantial or inferential in nature. Nevertheless, taken together, such lines of evidence may be quite convicing.

Eruption of lava from fracture zones suggestive of incipient ring fractures.—The distribution of the domes and flows indicates that they were erupted along arcuate zones. Vents for the porphyritic units trace nearly 360° of a circle approximately 12 km in diameter, with a smaller arc concentric within it. Vents for the younger aphyric lavas define 250° of a circle approximately 14 km in diameter, the center of which is displaced southward from that

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* Bailey and MacDonald (1975) reached a similar conclusion in their study of a suite of peralkaline obsidians from Eburru volcano, Kenya Rift Valley. Major and trace element variations could not be explained by closed-system crystal fractionation or fractional melting, and they argued that the magmas must have been generated in an open system with a halogen-bearing vapor phase buffering the composition of the melts.

of the porphyritic units. Studies of ash flow complexes have shown that precursory volcanic activity is often localized along arcuate fracture zones thought to result from regional intumescence accompanying the shallow emplacement or growth of the underlying magma chamber (Williams, 1942; Bailey *et al.*, 1976). During the climactic ash flow eruption, this zone of weakness becomes the ring fault along which the cauldron block subsides.

Nature of the faulting.—All exposed faults in La Primavera complex begin and end within the environs of the Sierra La Primavera; no faults extend beyond the Sierra to offset older rocks. This suggests that faulting is not the result of large-scale regional tectonics, but rather is the product of forces localized within the Sierra La Primavera. The gently arcuate normal faults of La Primavera complex are not dissimilar to the fracture patterns produced in experimental work on doming (Cloos, 1939), or on domes within resurgent cauldrons (Smith and Bailey, 1968); there is even a suggestion of an apical graben in the small graben that crosses the south end of Mesa El Nejahuete. Further support for such faulting being the result of regional intumescence is found in a study of the Timber Mountain caldera, Nevada (Christiansen *et al.*, 1965). There, early doming produced a zone of "circumferential extension faults" geometrically related to the later ring fracture zone.

Radial flow directions of the aphyric coulees.—From the sketch map (Figure 2) it is apparent that the aphyric couless of the southern fracture zone all flowed radially away from the center of the complex. There are no exposures of older rocks that might have formed a preexisting ridge for the lava to flow down; in fact, all evidence suggests that prior to La Primavera volcanism, the area was a basin. Intumescence, which could have produced the southern ring fracture zone, also could have provided a slope which the aphyric lavas could flow down. The porphyritic lavas do not show this strong orientation of flow directions; instead they spread in all directions to form domes. This seems to indicate a major episode of intumescence just prior to the eruption of the aphyric units about 60,000 years ago.

Radial dips of lake beds and planar topographic surfaces.—The origin, and disposition of the ashy lake beds within the central region of the Sierra La Primavera is critical to an understanding of the deformational history of the complex. These lake beds are high in the pyroclastic section, well above the level of the present Guadalajara basin. If the lake beds were originally deposited at a level equivalent to the surrounding basins of Guadalajara and Presa de La Vega (where similar lake beds are abundantly exposed), then uplift of at least 200 m is required to raise them to their present elevation. (It should be noted that such a hypothesis seems to require that at least some of the domes were erupted through water). The alternative to this hypothesis is that the domes and flows themselves may have formed an enclosed basin within which a lake may have formed. Clearly, such closure does not exist today, and it does not appear likely that it ever existed. If it had, a considerable portion of the domes must have been subsequently removed by erosion to produce their present shapes. Preservation of the pumiceous carapace on most of the domes indicates that they have been little eroded and that their present configuration is very similar to the original. In any case, at least a small amount of deformation is required to produce the observed 2° eastward dip on the 5 m lake bed between Mesa El Nejahuate and Mesa La Lobera.

Capping the central region is a planar surface, the great lateral extent of which would seem to preclude its being a surface of erosion in an area of high rainfall; it seems more likely that it was an originally horizontal surface of deposition within a basin. This surface was then uplifted, tilted, and deeply incised. The most recent uplitf may be represented by the fresh-looking scar in the lavas of Cerro El Pedernal along the trace of the Río Caliente fault, and by 30 m cliffs forming the lower banks of rejuvenated arroyos in the central region. This uplift of the central region and the tilting of lake beds and other planar surfaces may be best explained by doming accompanying volatile build-up or continued growth of a shallow magma chamber.

The presence of a "shadow zone".—In silicic caldera complexes such as those of the Yellowstone Plateau (Christiansen, in preparation), Long Valley, California (Bailey *et al.*, 1976), and Valles, New Mexico (Smith and Bailey, 1968b), basaltic eruptions cease in an area once silicic volcanism is underway. Basaltic eruptions may continue peripheral to the silicic center, but they will begin again in the central area only after the silicic volcanism has ceased. This effect is atributed to the "shadow zone" produced by a magma chamber; basaltic magma being denser, cannot rise through silicic magma, and will crystallize at depth. Once the silicic magma chamber cools sufficiently to sustain brittle fracture, basalts can once again erupt at the surface. No basalts or andesites have erupted through the Sierra La Primavera in at least 100,000 years, although basaltic eruptions preceded the silicic volcanism in the area and continued to the northwest at Volcan Tequila and to the south and southeast in smaller but more numerous cones, coeval with La Primavera volcanism. The lack of basic volcanic activity in the Sierra La Primavera may be attributed to a "shadow zone" produced by an underlying silicic magma chamber.

Hot spring and fumarolic activity.—Hot spring and fumarolic activity is concentrated in the Sierra La Primavera relative to the surrounding countryside. Heating and circulation of such a large volume of water would certainly be aided by the presence of a shallow-level magma chamber.

Comparison with ash flow and ring dike complexes.—If the vents for La Primavera lavas are indeed located along incipient ring fracture zones, they circumscribe an area similar in size to that contained within the inner ring fractures of cauldrons such as the Valles, New Mexico (Smith and Bailey, 1966), Creede, Colorado (Steven and Ratté, 1965), and Timber Mountain; Nevada (Byers *et al.*, 1976), and to that encompassed by many granitic ring dikes. A striking example of the latter is found in the Liruei complex of northern Nigeria, where, prior to collapse of the complex and injection of ring dikes, phenocryst-poor, comenditic lavas and pyroclastic ejecta were erupted along a 12 × 15 km incipient ring fracture zone (Jacobsen *et al.*, 1958).

No single piece of evidence unequivocally requires the presence of a shallow-level magma chamber beneath the Sierra La Primavera. Nevertheless, numerous inter-related geochemical and physical features are explained best as manifestations of the shallow-level emplacement, growth, and chemical evolution of a magma chamber.

DISCUSSION

The Sierra La Primavera, as the site of an evolving silicic magma chamber, is of considerable interest for both scientific and practical reasons. La Primavera complex may provide a striking example of the intumescent stage of a cauldron cycle (Smith and Bailey, 1868a). In La Primavera complex it is possible to document intumescence and establish the time frame in which it occurred (or perhaps is still occurring). Linked to the structural and volcanic history are the changes in chemistry of the eruptive products, which give periodic progress reports on the differentiation processes proceeding at depth. By being able to observe some of the intermediate stages in the development of a high-silica magma, rather than only the final voluminous product, the ash flows, it may be possible to devise more accurate models of differentiation. The period spanned by the eruptive units may yield important information about the rate of differentiation, as well as place constraints on the types of mechanisms possible. The interpretation of chemical analyses now in progress, in conjunction with further field studies, will lead to a fuller explanation of the physical and geochemical evolution of La Primavera complex and hopefully shed new light on the processes that produce high-silica magmas.

Of more immediate concern to the residents of the surrounding region is the potential for good and bad associated with La Primavera complex. The recency of this silicic volcanic activity, the probable presence of a 14 km diameter magma chamber, and the circulation of large volumes of heated water suggest there is an abundant supply of heat energy available now and for tens of thousands of years to come. Add to this the proximity to the metropolitan area of Guadalajara and La Primavera complex becomes a very attractive target for geothermal development.

With this blessing comes potential danger. There is no reason to believe that volcanic activity has ceased. Permanent damage from the erpution of a new dome would be limited to where the dome emerged, but the surrounding area would be mantled by air-fall pumice to a depth of several meters. Much more catastrophic in terms of loss of life and property would be an ash flow eruption. By comparing the volume of material erupted in ash flows with the area of the magma chamber (assuming it is equal to the projected area inside the ring fault), Smith (1976) has shown that in most systems the eruption is equivalent to a 1 km draw-down of the magma chamber. Assuming the circle traced by the aphyric units in an incipient ring fracture zone, the volume of magma which could potentially be erupted in ash flows from La Primavera complex might be as much as 200 km^3. The ground-hugging ash flow portion of the eruption would fill the surrounding basing to a depth of more than 100 m in tuff; the accompanying cloud of ash and hot gas would rise to great heights, causing destruction over an even larger area. Even an eruption only one-tenth the size of that possible could destroy Guadalajara! In general, the period of time between inception of volcanism along the incipient ring fracture and the climactic ash flow eruption in large silicic systems is relatively long, *e. g.*, 0.6 and 1.2 million years, respectively, for the Yellowstone and Long Valley systems (Christiansen, in preparation; Bailey, 1976). Thus the chance of an ash flow eruption occurring in the near future is slim. Nevertheless, given the potential disaster, the Sierra La Primavera may warrant the use of modern, volcanic hazard monitoring techniques.

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