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THE IGNEOUS HISTORY OF THE SIERRA MADRE OCCIDENTAL AND ITS RELATION TO THE TECTONIC EVOLUTION OF WESTERN MEXICO

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ABSTRACT

Igneous rocks of the Sierra Madre Occidental have been mapped and dated along latitude 24° N between Mazatlán and Durango City and near latitude 28° N in Chihuahua. In both of these regions and probably throughout the Sierra Madre Occidental are found two vast and largely coextensive igneous sequences, both calcalkalic and both including ignimbrites, but otherwise dissimilar. The older sequence, ranging in age from 45 m.y. to at least 100 m.y., contains abundant batholithic as well as volcanic rocks dominantly of intermediate composition. The younger sequence is dominated by rhyolitic ignimbrites erupted from numerous large caldera complexes. Smaller outpourings of basaltic lava accompanied the ash flows, but intermediate rocks are rare. Most of the volcanism was confined to a brief interval 34 to 27 m.y. ago.

Some of the older volcanic rocks are interfingered with marine Cretaceous sediments. Pronounced uplift and mild deformation occurred by early Tertiary time, and erosion provided voluminous debris to basins east of the Sierra Madre Occidental. Magmatism declined about 45 m.y. ago and resumed vigorously about 34 m.y. ago, producing widespread ignimbrite sheets with minor lava flows.

Although most of the major gold and silver veins are closely associated with the older volcanic rocks, they are commonly related to younger caldera structures and a few occur within the mid-Tertiary rocks. Many small tin deposits and a few large iron deposits are genetically related to the mid-Tertiary rocks.

The older volcanic and plutonic rocks were emplaced along the continental margin during convergence in Cretaceous and early Tertiary time. The batholiths of that sequence comprise much of the craton beneath the western part of the Sierra Madre Occidental. The diminution of magmatism between 45 and 34 m.y. ago and the subsequent abrupt onset of dissimilar volcanic activity do not correspond well with known Pacific sea-floor spreading events. Volcanism declined about 27 m.y. ago when subduction began to terminate.

The association of rhyolite ignimbrite with subordinate basalt and minimal andesite may be due to remelting of underlying batholithic rocks by rapidly rising basalt during mid-Tertiary subduction.

RESUMEN

Las rocas ígneas de la Sierra Madre Occidental fueron cartografiadas y fechadas a lo largo de la latitud 24° N entre las ciudades de Mazatlán y Durango, así como en el Estado de Chihuahua, cerca de la latitud 28° N. En ambas regiones y probablemente en toda la sierra, se registró la existencia de dos grandes secuencias de rocas ígneas, casi co-extensas. Ambas secuencias son calco-alcalinas y contienen ignimbritas, pero son diferentes en otros aspectos. La secuencia inferior, cuyas edades varían desde 45 m.a. hasta al menos 100 m.a., contiene abundantes rocas batolíticas y volcánicas principalmente de composición intermedia. La secuencia superior está formada predominantemente por ignimbritas riolíticas originadas a partir de calderas numerosas y grandes. Estas extrusiones cineríticas estuvieron acompañadas por pequeñas emanaciones de lava basáltica y raramente por rocas intermedias. La mayor parte de este volcanismo estuvo confinada a un corto intervalo, entre 34 y 27 m.a.

Algunas rocas volcánicas de la secuencia inferior se interdigitaron con sedimentos marinos del Cretácico, y ocurrieron fuertes levantamientos tectónicos acompañados por ligeras deformaciones antes del Terciario temprano, con la erosión subsecuente que suministró grandes volúmenes de clásticos a las cuencas situadas al oriente de la Sierra Madre Occidental. Este episodio magmático-volcánico casi se extinguió hace aproximadamente 45 m.a., para volver a reactivarse vigorosamente hace aproximadamente 34 m.a., produciendo las ignimbritas distribuidas ampliamente con menores cantidades de derrames de lava.

Aunque la mayoría de las vetas de oro y plata está íntimamente asociada con rocas de la secuencia inferior, ellas están comúnmente relacionadas con las estructuras geológicas producidas por la formación de las calderas más jóvenes. Asimismo, algunas de estas vetas se presentan dentro de las rocas de la secuencia superior. Existen muchos depósitos pequeños de estaño, genéticamente relacionados con las rocas jóvenes y unos pocos, pero grandes, depósitos de fierro.

Las rocas plutónico—volcánicas más antiguas se emplazaron a lo largo de una margen continental que estuvo sujeta a convergencia durante el Cretácico y Terciario temprano. Los batolitos de esta secuencia componen gran parte del cratón que existe debajo de la parte occidental de la Sierra Madre Occidental. La disminución del magmatismo en el intervalo entre 45 y 34 m.a., con la subsecuente aparición abrupta de una actividad volcánica diferente, no corresponde a eventos conocidos de tectónica global. Este volcanismo decreció hace aproximadamente 27 m.a., justo cuando el proceso de subducción comenzó a disminuir.

La asociación de ignimbritas riolíticas a cantidades subordinadas de basalto y mínimas de andesita, pudo deberse a la refusión de las rocas batolíticas subyacentes, producida por el ascenso rápido de magma basáltico durante la subducción del Terciario medio.

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INTRODUCTION

During the past 100 million years the Sierra Madre Occidental and surrounding regions of mainland Mexico have been the scene of two major episodes of igneous activity (McDowell and Clabaugh, 1979). Field studies by ourselves, our colleagues and students, and by other workers during the past 10 years in the states of Sinaloa, Durango, Chihuahua and Sonora (Figure 1) have increased our understanding of these major events and their significance in relation to regional tectonics and ore deposits. Geochronology, isotopic studies, and major-element chemical analyses allow a comparison of the magmatic history of the Sierra Madre Occidental to that of other circum-Pacific regions.

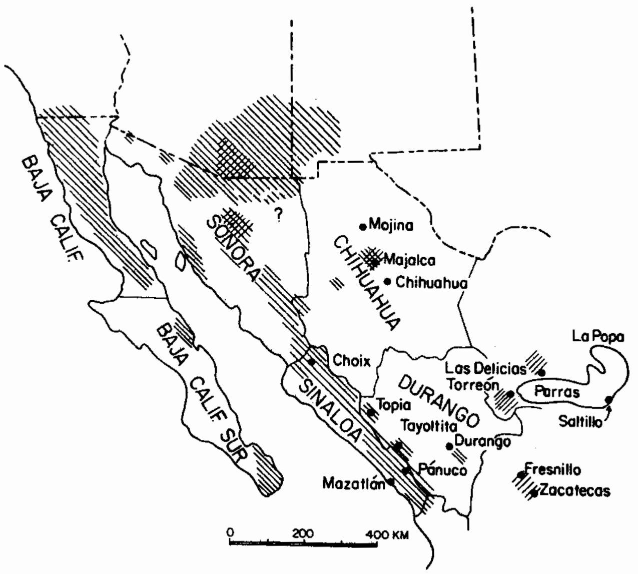

Figure 1.- Distribution of intrusive and volcanic rocks of Late Cretaceous-early Tertiary (ruling slopes down to right) and older Mesozoic (down to left) ages in western Mexico and adjacent United States. The positions of the Parras and La Popa basins, which received debris from eroding highlands of the lower volcanic complex during the Late Cretaceous-early Tertiary, are shown. Localities mentioned in the text are shown.

The earlier of the two major igneous episodes is represented by ignimbrites, lavas, and composite batholiths. The batholiths are best exposed on the coastal plain of mainland Mexico adjacent to the Sea of Cortés and in the deep canyons that reach eastward into the Sierra Madre Occidental. Ages determined by Henry (1975) for batholithic rocks in Sinaloa range from Late Cretaceous through early Tertiary (102 to 45 m.y. ago). The intrusive rocks are at least partly coeval with thick accumulations of volcanic rocks, generally similar in composition but commonly so altered that meaningful chemical analyses and potassium-argon dates are difficult to obtain. These batholithic and associated extrusive rocks have been called the *lower volcanic complex* (McDowell and Keizer, 1977). They are the probable continuation of younger parts of the Sierra Nevada and Peninsular Ranges batholiths.

An extensive sequence of ignimbrites with interlayered lava flows and tuffaceous sediments overlies the lower volcanic complex and forms the crestal plateau of the Sierra Madre Occidental (Figure 2). This great accumulation of mid-Tertiary volcanic rocks has been informally designated the *upper volcanic supergroup* (McDowell and Keizer, 1977). It is comparable to ash-flow tuffs and associated rocks of similar age that blanket wide areas of the western United States.

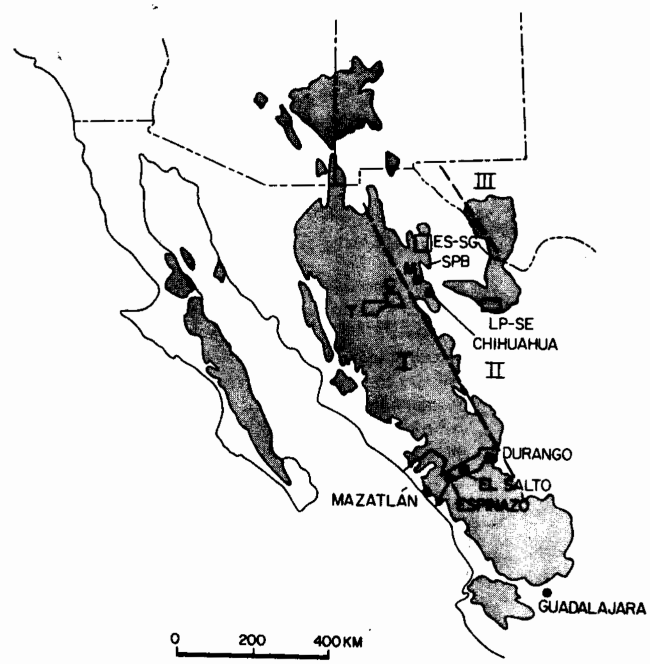

Figure 2.- Generalized distribution of volcanic rocks of middle Tertiary age in western Mexico and adjacent United States. Zone I is the upper volcanic supergroup province in the Sierra Madre Occidental, Zone II is the eastern Chihuahua and westernmost Texas provinces, and Zone III is the alkalic province of Trans-Pecos Texas (see text). Mapping projects and localities mentioned in the text are shown. LP-SE = La Perla-Sierra Encinillas; ES-SG = El Sueco-Sierra Gallego; SPB = Sierra Peña Blanca; M = Majalca; C = Cuauhtémoc; T = Tomóchic.

In western Mexico these two igneous suites occupy similar areas; they are nearly superimposed throughout most of the Sierra Madre Occidental (Figures 1 and 2). Both are approximately parallel to the western continental margin. To the north in the western United States, the distribution of Mesozoic and Tertiary igneous rocks clearly does not follow this simple pattern, and attempts to relate them to a simple tectonic model of the continental margin have met with difficulties. Although the geometry in western Mexico is more regular, the data base for interpreting genesis and chemical evolution of the igneous rocks is much smaller.

Equally as significant as the igneous rocks themselves is the striking evidence for a major unconformity between the two igneous sequences. Recent assertions (Clark *et al.*, 1978) of a continuity of magmatism in western Mexico from about 130 m.y. ago to the present are in clear disagreement with field evidence of a period of restricted magmatism. Chronologic evidence suggests that this period of limited magmatism was relatively brief; it may not have occurred everywhere at the same time. Nevertheless it appears in the geologic record over a wide area of western Mexico. Future study of its timing and distribution will be a critical contribution to the tectonic history of the region. For the present we can only underline its existence and emphasize its importance.

IGNEOUS GEOLOGY

FIELD AND AGE RELATIONSHIPS

Lower Volcanic Complex.- A very significant study of a large area of the Cretaceous-early Tertiary igneous rocks of western Mexico was made by Fredrikson (1974) and Henry (1975) in Sinaloa. Many detailed studies of igneous rocks in smaller areas surrounding major ore deposits have been made throughout the Sierra Madre Occidental by numerous geologists, but only a few of the most recent include age determinations.

Dark andesitic rocks seem to dominate the extrusive portion of the lower volcanic complex, but careful examination in several places has shown nearly equal amounts of intermediate and silicic rocks. The proportions of flow rock and volcaniclastic sediments vary widely. In sharp contrast with the mid-Tertiary volcanic rocks that cap the Sierra Madre Occidental, the older rocks tend to be more deformed by faulting, tilting and gentle folding, and are typically highly altered. Indeed, they are host to a major fraction of Mexico's mineral deposits, and at least a trace of sulfides can be found in nearly every large outcrop.

At Tayoltita (Figure 1) the canyon of the Río Piaxtla exposes more than 2,000 m of volcanic rocks intruded at the base of the section by a granodiorite batholith. Two major rhyolitic ash flows comprise at least 800 m of the section, but andesite is the chief host for gold-silver veins in the Tayoltita-San Dimas district, as in most other precious metal deposits in the region. Some of the volcanic rocks and associated andesite dikes display very low-grade metamorphism characterized by pumpellyite and prehnite (Nemeth, 1976).

At the Topia mining district in northern Durango (Figure 1), Lemish (1955) described at least 1,400 m of tilted volcanic rocks dominated by andesite flows, pyroclastic rocks and breccia containing clasts of older rhyolite. In northern Sinaloa only andesitic rocks were described by Bonneau (1971), Fredrikson (1971) and Clark (1976), but at localities in southern Sinaloa and western Chihuahua (Clark *et al.*, 1979) extrusive rocks of the lower volcanic complex range from dominantly rhyolitic rocks to nearly equal amounts of rhyolite and andesite flows and pyroclastic deposits.

Evidence of the age of volcanic rocks assigned to the lower volcanic complex is largely indirect. The rocks studied so far are generally too altered even for satisfactory petrographic study. In a few localities, andesitic rocks are interbedded with fossiliferous Cretaceous limestone, as recorded by King (1939) in Sonora and westernmost Chihuahua, and by Bonneau (1969) in Sinaloa. In adjacent areas of the United States, Drewes (1971) has described Lower Cretaceous volcanic rocks from the Santa Rita Mountains of southern Arizona, and Hayes (1970) has reconstructed an extensive Upper Cretaceous field in southeastern Arizona and southwestern New Mexico, extending southward an undetermined distance into Mexico.

East of the Sierra Madre Occidental, the lower volcanic complex is exposed only sporadically, and evidence of age is sparse. Mauger (1977) has found two older sequences of volcanic rocks below an upper Eocene ash flow in Majalca Canyon, north of Chihuahua City (Figure 2). These are similar in deformation and degree of alteration to rocks of the lower volcanic complex, but as yet they are undated. A K-Ar age of 52 m.y. was obtained from andesitic rocks lying beneath the mid-Tertiary ignimbrites south of Durango City (McDowell and Keizer, 1977).

Close spatial association of the lower volcanic rocks with batholiths along the western flank of the Sierra suggests, but does not prove, a common origin. Where the volcanic rocks are in contact with intrusive rocks, the intrusions are almost always younger. Batholithic rocks that intrude volcanic rocks are as old as 65 m.y. near Tayoltita, 57 m.y. at Pánuco (Henry, 1975), 60 m.y. at Choix in northern Sinaloa (Clark, 1976), 63 m.y. at Maicova in western Chihuahua (Bockoven, in progress), and as young as 45 m.y. at Tayoltita (Henry, 1975).

The extensive U-Pb and K-Ar chronology of the batholithic rocks in southern Sinaloa documents a virtually continuous period of magmatism from 102 to 45 m.y. ago (Henry, 1975). Many of the 102-85 m.y.-old intrusive rocks show evidence of syntectonic deformation, whereas the younger plutons do not. Henry determined that the Cretaceous-Tertiary plutons of southern Sinaloa generally become less mafic and younger to the east. Isotopic ages of similar intrusive and related volcanic rocks range from 75 to 52 m.y. in northern Sinaloa (Salas, 1975), from 140 to 80 m.y. in the Peninsular Ranges batholith of southern California and Baja California (Silver, 1979; Gastil *et al.*, 1975), and from 97 to 50 m.y. in central and northern Sonora (Anderson and Silver, 1974; Salas, 1975; Gastil and Krummenacher, 1977). In the eastern part of the Peninsular Ranges batholith and in northern Sonora, the isotopic ages also decrease progressively from west to east, but over a much wider belt than found by Henry.

Upper Volcanic Supergroup.- The Sierra Madre Occidental is a vast high plateau that forms the western margin of the central upland of Mexico. It is deeply dissected by west-flowing rivers that descend rapidly to sea level, and remnants stand as high ridges and rugged peaks isolated by deep canyons. The plateau is capped by nearly flat-lying mid-Tertiary volcanic rocks, among which rhyolitic ignimbrites are spectacularly exposed. It probably displays the largest continuous ignimbrite expanse in the world in a southeast-trending belt approximately 250 km wide and 1,200 km long (Figure 2). To the south it disappears beneath the cover of younger volcanic rocks near Guadalajara. The volcanic rocks of this region continue beyond the Sierra Madre Occidental into fault-bounded mountains along both the northeastern and the southwestern margins of the plateau.

Volcanic rocks of the upper volcanic supergroup have long been recognized and shown on geologic maps of Mexico; Ordóñez published two volumes (1900, 1901) on the rhyolites of Mexico, with considerable emphasis on those of the Sierra Madre Occidental and with photomicrographs showing the textures of ignimbrites. But these rocks received no detailed field studies, in part because they contain few ore deposits, until J. Hoover Mackin encouraged Waitt (1970) to study the ignimbrites that are boldly exposed along the central part of the Durango City-Mazatlán highway (Figure 2) which is still the only major road across the Sierra Madre Occidental. The highway provided access for a series of mapping projects that span the sierra and were done under our supervision (Wahl, 1973; Keizer, 1973; Swanson, 1974; Lyons, 1975). Current studies in Chihuahua by several groups of investigators are rapidly adding information on the northern part of the Sierra Madre Occidental (Swanson, 1977; Keller, 1977; Bockoven, 1976; Cameron and Cameron, 1976; Campbell, 1977; Mauger, 1977; Spruill, 1977; Megaw, 1979; Bagby, 1979; Bockoven, in progress; Duex, in progress).

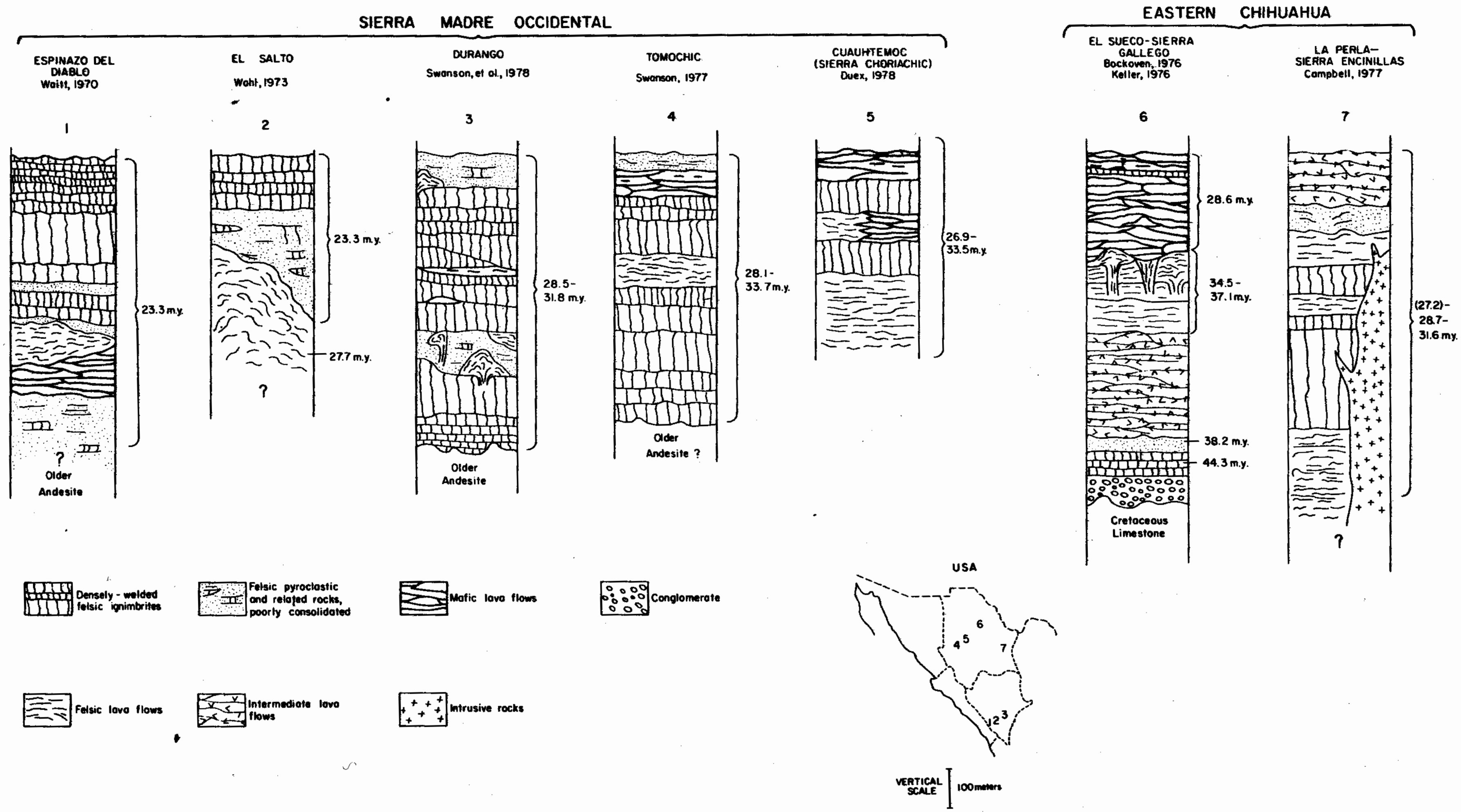

Figure 3.- Generalized stratigraphy and K-Ar ages for rocks of the upper volcanic supergroup in five areas in the Sierra Madre Occidental and for similar volcanic rocks in two areas in eastern Chihuahua.

Schematic stratigraphic sections, along with ranges of K-Ar dates, are given for five mapped areas in the Sierra Madre Occidental and two others in eastern Chihuahua (Figure 3). Moderately to densely welded, rhyodacitic to rhyolitic ignimbrites are the dominant rocks. Subordinate amounts of mafic rock are usually present, mostly at or near the top of the section. The ages and field relationships of the mafic lavas clearly show them to be associated closely with the more felsic rocks.

In each area nearly all volcanic rocks were emplaced within a short time, typically 3 to 5 m.y., and an age range of 34 to 27 m.y. encompasses most of this volcanic activity. At Espinazo del Diablo and El Salto, the westernmost sections along the Durango-Mazatlán traverse, all the ignimbrites and lava flows yield the same K-Ar age, 23 m.y., within experimental error (McDowell and Keizer, 1977). These rocks appear to belong to a single source or a closely related group of sources. Near Yécora in eastern Sonora a thick sequence of basalts with interlayered rhyolitic tuffs is also about 23 m.y. old (Bockoven, in progress). Large ignimbrite sheets of this age are evidently much less common than those 34-27 m.y. old. Even at El Salto, flow domes 28 m.y. old at the base of the section (Figure 3) appear to be related to thick ignimbrites exposed in a deep barranca to the south.

Of the volcanic sections studied in eastern Chihuahua (Figure 3), that at La Perla-Sierra Encinillas is similar in age and field relationships to those of the Sierra Madre Occidental. The section at El Sueco-Sierra Gallego differs in that parts of three volcanic sequences are present. The oldest is a succession of thin ash-flow tuffs that is probably correlative with rocks at Sierra Peña Blanca, 80 km to the south (Figure 2). These range in age from 45 to 37 m.y. (Alba and Chávez, 1974; Keller, 1977); rhyolitic tuffs of similar age have been studied near Majalca (Mauger and McDowell, unpublished data). A thick sequence of andesitic to rhyodacitic flows and rhyolitic domes and flows was emplaced 35 to 38 m.y. ago at El Sueco-Sierra Gallego. Following a 6 m.y. hiatus, extensive basalt flows, accompanied by a thin rhyolitic ignimbrite, were erupted 28.5 m.y. ago. Only this last sequence coincides with the peak of Sierra Madre Occidental volcanism.

In the Sierra Pastorias south of Chihuahua City two resurgent calderas, one about 22 km in diameter and the other about 10 km in diameter, produced extensive rhyolitic ash flows that are similar to those of the Sierra Madre Occidental to the west (Megaw, 1979). Basalt flows rest unconformably on the ash flows adjacent to the calderas.

Farther eastward in west Texas dominantly alkalic volcanism began about 45 m.y. ago and persisted until 20 m.y. ago (McDowell, 1979). This activity began earlier and continued later than magmatism in the Sierra Madre Occidental (Figure 4). However, the period of intense volcanism in the Sierra is also a time of maximum igneous activity in west Texas.

Younger Rocks.- The volume of igneous activity declined sharply after 23 m.y. ago in the Sierra Madre Occidental. Volcanism continued throughout the Miocene to the west of the Sierra Madre Occidental at several localities on the present mainland coast and in Baja California, where the Comondú Formation covers large areas (Gastil *et al.*, 1979). Most of these volcanic rocks are petrographically and chemically different from the upper volcanic supergroup of the Sierra Madre Occidental.

Near Durango City, nepheline-normative alkali basalts accompanied Basin and Range style of faulting about 12 m.y. ago (McDowell and Keizer, 1977; Swanson *et al.*, 1978).

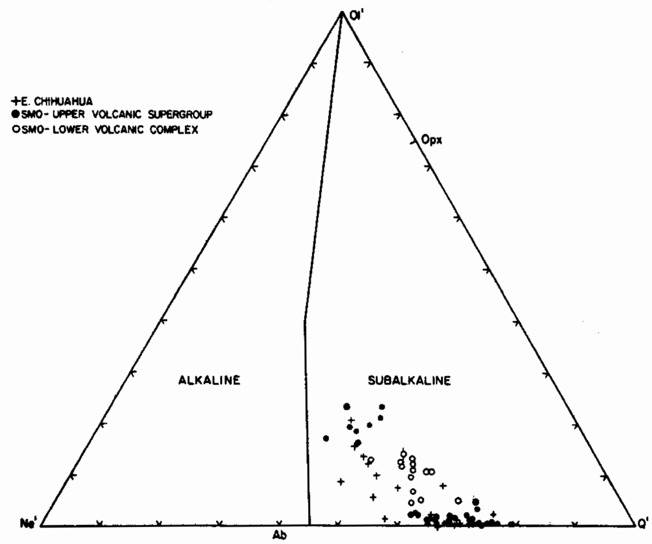

Figure 4.- Ol'-Ne'-Q' plot for analyzed rocks from western Mexico. Plot is after Irvine and Baragar (1971). Because of overlap, not all available analyses are plotted.

Basaltic rocks of Late Tertiary and Quaternary age are widespread in western Mexico. They are common in northern Sinaloa (Fredrikson, 1971) and north of Mazatlán (Fredrikson, 1974; Henry, 1975), and Quaternary basalt covers the surface of a large area in the Guadiana Valley (Figure 5) in southern Durango (Albritton, 1958; Swanson *et al.*, 1978). The distribution and tectonic implications of these rocks remain largely unstudied.

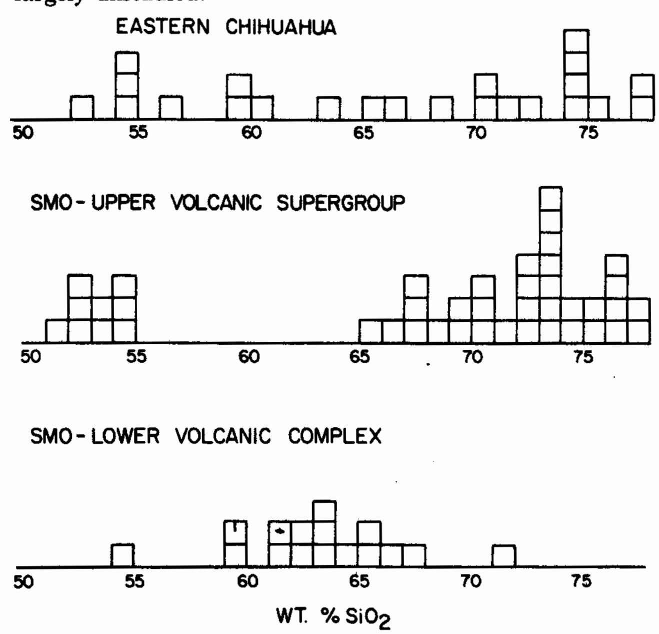

Figure 5.- Histogram of SiO_2 contents for volcanic rocks of western Mexico. Note the absence of analyses with SiO_2 between 55 and 65 percent for the upper volcanic supergroup. Analyses from lower volcanic complex are of batholithic rocks except for one (marked with a tick).

CHEMISTRY

Eighty volcanic rock samples from the Sierra Madre Occidental and adjoining areas have been analyzed for 13 major-element oxides by wet chemical techniques. Forty-two samples are from the main Sierra Madre Occidental (region I of Figure 2) and 23 are from eastern Chihuahua (region II). In addition, for the lower volcanic complex a single analysis of an andesite (Swanson *et al.*, 1978) and 14 analyses of batholithic rocks have been made (Henry, unpublished).

All 80 analyses are subalkalic, using the Ol'-Ne'-Q' triangular plot of Irvine and Baragar (1971) (Figure 6). All points are consistent with a calc-alkalic trend on an AFM diagram (not shown). All the rocks are quartz normative; one sample from La Perla-Sierra Encinillas is peralkalic.

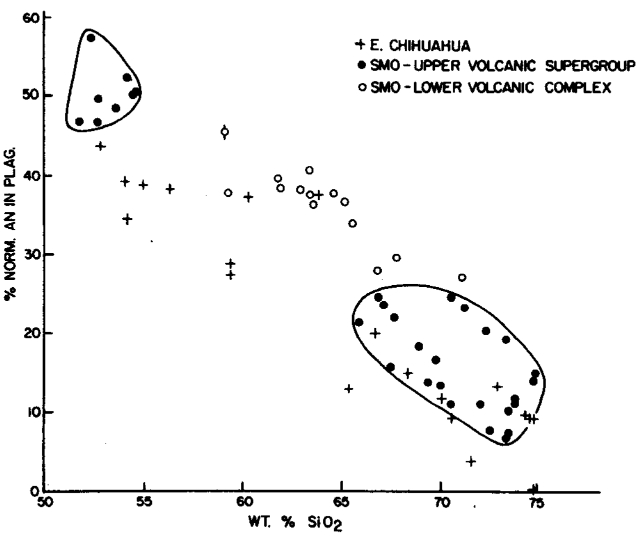

Figure 6.- Percent normative An in plagioclase versus percent SiO_2 for analyzed volcanic rocks from western Mexico. All analyses from the upper volcanic supergroup fall within the two widely separated fields.

A striking bimodality is evident for the upper volcanic supergroup. None of the 42 analyses contains between 55 and 65 percent SiO_2 (Figure 7). Although this compositional interval appears reasonably well represented in eastern Chihuahua, three of the five analyzed rocks with this composition exhibit fritted plagioclase textures that may indicate a hybrid origin (Bockoven, 1976; Campbell, 1977). Thus, intermediate rocks appear to be very rare in the upper volcanic supergroup of the central belt of the Sierra Madre Occidental, and they probably are sparse in eastern Chihuahua.

A plot of normative plagioclase composition versus percent SiO_2 (Figure 8) shows that the mafic rocks of the Sierra Madre Occidental are distinctly higher in An than those of eastern Chihuahua. This appears to be true also for felsic rocks, but the distinction diminishes with increasing SiO_2 content. In an alkalinity diagram (Figure 9), both mafic and felsic rocks of the Sierra Madre Occidental can be distinguished clearly from rocks with similar SiO_2 content from the alkalic province of Trans-Pecos Texas (Barker, 1977). Analyzed rocks from eastern Chihuahua and from a belt of metaluminous rocks (Barker, 1977) adjacent to the Río Grande in Texas (both in region II of Figure 2) fall generally between these two groups, but show more overlap with the Sierra analyses. Thus, three distinct, broad bands of volcanic rock of generally similar age and character can be distinguished on the basis of alkalinity ratio. These are, from west to east, calc-alkalic Sierra Madre Occidental proper (region I, Figure 2), intermediate eastern Chihuahua and adjacent Texas (region II) and alkalic Trans-Pecos Texas (region III). The rocks of region II are clearly calc-alkalic, therefore the most pronounced compositional change may occur within Texas.

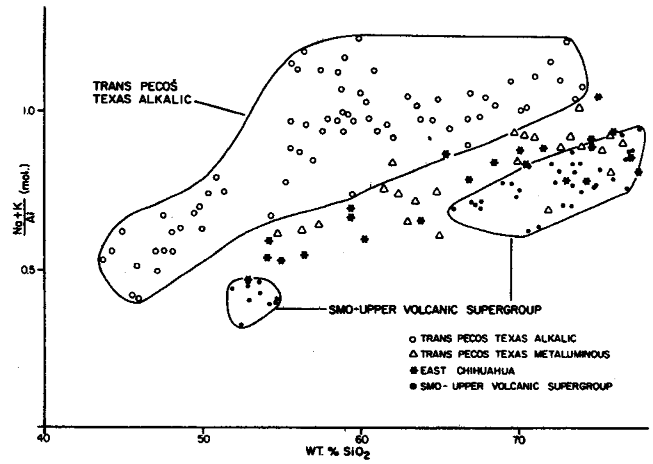

Figure 7.- Alkalinity (mole percent Na + K)/Al) versus percent SiO_2 for Tertiary volcanic rocks of the upper volcanic supergroup, eastern Chihuahua belt, metaluminous Trans-Pecos Texas belt, and alkalic Trans-Pecos Texas province. The points from Texas are from Barker (1977).

Comparison of the chemistry of the lower volcanic complex with the upper volcanic supergroup is difficult because of limited compositional overlap among the available analyses. From analyses of the batholithic rocks it appears that the lower volcanic complex contains more normative An than the upper volcanic supergroup at the same SiO_2 content (Figure 8). Certainly, the dominantly intermediate lower volcanic complex is more typical of an island arc-continental margin calc-alkalic suite than is the bimodal upper volcanic supergroup.

MAJOR TECTONIC FEATURES

LARAMIDE DEFORMATION AND UPLIFT

Uplift, deformation, and intensified erosion occurred in western Mexico from Late Cretaceous through early Eocene time. Folding in the Chihuahua tectonic belt has been attributed to eastward sliding of Cretaceous beds on underlying salt and gypsum when uplift occurred to the southwest (DeFord, 1969). Uplift is also indicated by the great volume of volcanic debris transported eastward during Late Cretaceous and Paleocene time into the Parras and La Popa Basins (Figure 1) (McBride *et al.*, 1974). Uplift appears to have progressed northeastward from the coastal region where deep erosion uncovered the batholithic rocks prior to Oligocene time.

The unconformity between the lower volcanic-plutonic complex and the overlying mid-Tertiary volcanic rocks is conspicuous in most parts of the Sierra Madre Occidental. It is usually marked by discordant attitudes of the rocks above and below, but even where this is not apparent, an abrupt down-

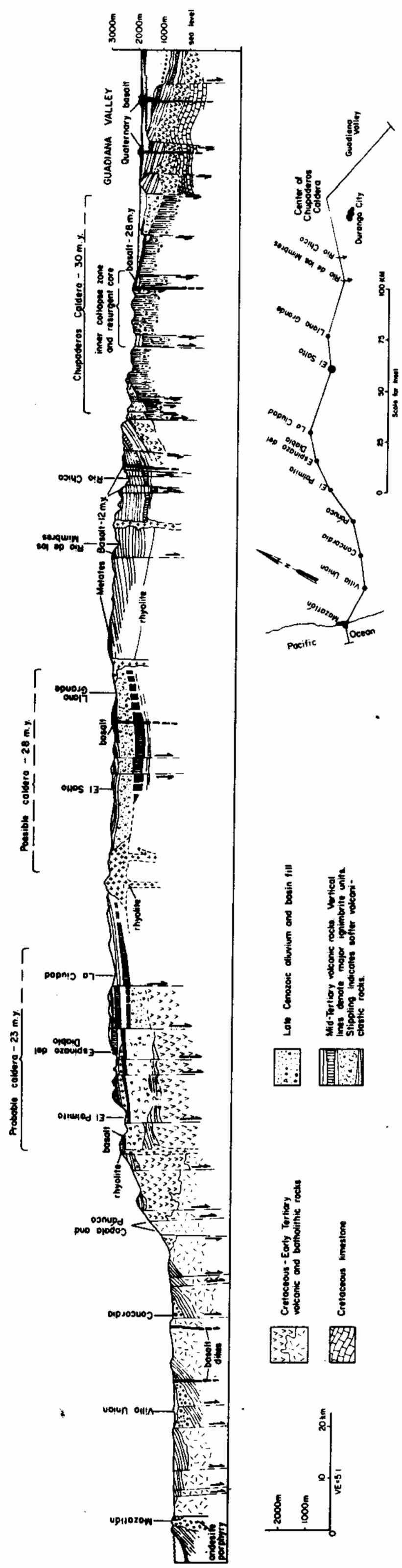

Figure 8.- Generalized cross-section of the Sierra Madre Occidental between Mazatlán and the Guadiana Valley.

ward increase in alteration is apt to be a reliable indicator of the unconformity. In the coastal region of Sinaloa interlayered rhyolite ignimbrites and andesites of the upper volcanic supergroup rest mainly on batholithic rocks. Northeast of Mazatlán at Tayoltita a red bed unit occurs between the upper and lower volcanic sequences. East of Mazatlán near Copala the basal part of the upper volcanic supergroup consists of interbedded tuffs, andesite and volcaniclastic sediments that attain great thickness in paleovalleys (Fredrikson, 1974; Henry, 1975). Much farther east near Durango City the basal ignimbrites of the upper group were deposited on a surface of considerable relief (Swanson *et al.*, 1978). At many localities on the eastern flank of the Sierra Madre Occidental the upper volcanic rocks rest unconformably on folded Mesozoic limestone.

CALDERAS WITHIN THE UPPER VOLCANIC SUPERGROUP

Detailed mapping of nearly 2,000 km² near Durango City and to the southwest revealed one large caldera complex (Swanson *et al.*, 1978), which produced at least three extensive ash-flow sheets, and indicated the presence of two other calderas. Mapping of about 3,000 km² in western Chihuahua similarly outlined two large calderas and found evidence of one other (Swanson, 1977; Bockoven, in progress). If these two samples are typical of the 250,000 km² central belt of the Sierra Madre Occidental, about 400 calderas are to be expected there! This suggested abundance of calderas is comparable to that in the central part of the San Juan volcanic field (Steven and Lipman, 1976). In areas where calderas have been mapped, as well as in orbital imagery of probable calderas (Muehlberger *et al.*, 1977), the structures are nearly circular and large; several exceed 40 km in diameter. Displacements along caldera-margin faults are typically about 1 km, therefore these are major structural features of the region.

Along the margins of the Sierra Madre Occidental, where mid-Tertiary ignimbrites generally extend a minimum of a hundred kilometers beyond the high Sierra, calderas are either uncommon or obscured by later faults and graben fill. Two moderately large calderas were documented south of Chihuahua City by Megaw (1979), and mid-Tertiary volcanic and clastic rocks examined by Mauger (1977) near Majalca resemble intracaldera deposits. Other studies east of the Sierra have revealed no calderas as yet. North of Chihuahua City at El Sueco-Sierra Gallego, Bockoven (1976), and Keller (1977) found prominent rhyolitic flowdomes aligned in a northwest trend, suggesting more passive, linear volcanic vents.

On the western side of the Sierra few calderas have been detected, but mapping has been on a regional scale. Moreover, younger faulting and alluvial deposits may obscure them. Fredrikson (1974) and Henry (1975) found no calderas in their reconnaissance mapping of 10,000 km² of southern Sinaloa.

POST-VOLCANIC STRUCTURES

A cross-section through the Sierra Madre Occidental and adjacent coastal plain from Durango to Mazatlán (Figure 5) illustrates general structure of the range and permits comparison with the section drawn by Clark (1976) for the Chihuahua City-Topolobampo strip, along the only railroad that crosses the Sierra. The cross section presented here is generalized and interpreted from sections prepared by students who mapped areas along the Durango-Mazatlán highway.

Approached from the northeast, the Sierra Madre Occidental appears to be an unimpressive homocline of very gently dipping mid-Tertiary volcanic rocks. They rise gradually toward the southwest from interior basins filled with younger deposits of unconsolidated sediment locally interbedded with Quaternary basalt flows. The 3,000 m crest of the range generally corresponds with the axis of a broad anticline. Dips generally steepen on the southwestern side of the range, and the continuity of the capping volcanic rocks is disrupted by major normal faults and by dramatic headward erosion of rivers draining into the Pacific Ocean.

The eastern flank of the range is also complicated by large faults, but younger deposits commonly obscure them. East of the Chupaderos caldera, in the Guadiana Valley, the cross section shows major faults beneath the cover of Quaternary alluvium and basalt. These faults are prominently exposed 60 km south of the line of section along the Sierra del Registro, a tilted fault-block range. This is part of the Basin and Range province along the eastern margin of the Sierra. The prominent zone of faults along the Río Chico Valley to the west of the Chupaderos caldera also has the regional N to NNW trend of Basin and Range faults, and basalt dikes and flows are closely associated with the faulting. The Metates Basalt lies unconformably on strongly faulted mid-Tertiary ignimbrites and was displaced less than rocks beneath it. Its emplacement about 12 m.y. ago occurred during Basin and Range faulting in this part of the Sierra (McDowell and Keizer, 1977). In the central part of the Sierra, faults are less common and displacement is minor. Almost all of these are normal faults, with the northeast side displaced downward. On the western side of the Sierra the faults are more prominent, with some displacements in excess of a kilometer. Several grabens preserve coarse upper Tertiary sediments that have been tilted and, in one roadside exposure, cut by a basalt dike (Fredrikson, 1974, p. 161).

ORE DEPOSITS

Our concern has been chiefly with the igneous rocks of the Sierra Madre Occidental, not with mineral deposits they contain. However, in some areas we have studied, ore deposits show close genetic ties with the igneous rocks that enclose them. Tin deposits in rhyolite ignimbrites of the region are small but numerous. The iron ore of Cerro Mercado in Durango is interpreted as lava flows of magnetite emplaced in the moat zone of a giant caldera about 30 m.y. ago (Lyons, 1975; Swanson *et al.*, 1978). Nearby smaller hematite deposits probably originated as ash flows of nearly pure iron oxide. Iron deposits farther north in eastern Chihuahua occur in volcanic rocks of virtually the same age as those at Cerro Mercado, but the largest (La Perla) appears to be chiefly of hydrothermal replacement origin (Van Allen, 1978). In the older volcanic and intrusive rocks a close genetic tie may be assumed for porphyry copper and molybdenum occurrences in the western part of the Sierra Madre Occidental and adjoining regions. In southwestern Mexico massive sulfide deposits are associated with volcanic rocks that probably formed in an island arc setting.

Rhyolitic rocks of mid-Tertiary age contain surprisingly few precious metal veins, whereas the altered andesites of the lower volcanic complex are the most common host rocks for gold and silver veins throughout the Sierra Madre Occiden-

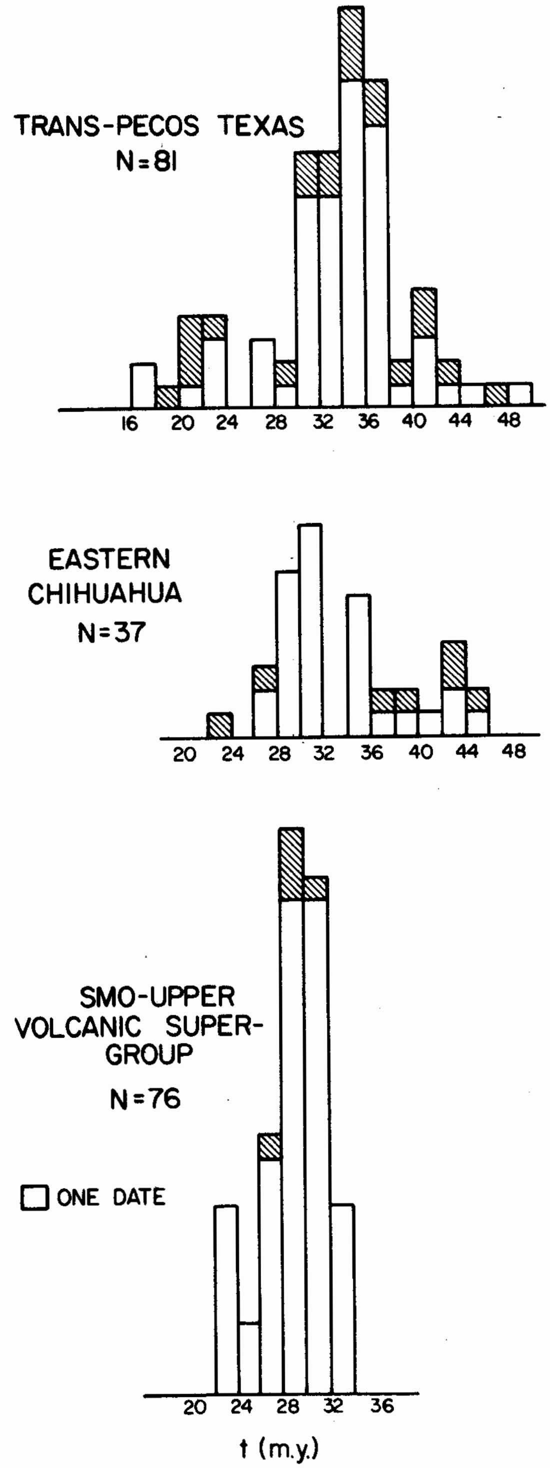

Figure 9.- Histogram of available K-Ar ages from the upper volcanic supergroup of the Sierra Madre Occidental, Tertiary volcanic rocks in eastern Chihuahua, and Tertiary volcanic rocks in Texas. Analyses *not* made at the University of Texas at Austin are diagonally ruled. Sources: Sierra Madre Occidental - McDowell and Keizer, 1977; Swanson, 1977; McDowell, unpublished; Salas, 1975; Clark and others, 1979. Eastern Chihuahua - Keller, 1977; Campbell, 1977; McDowell and Mauger, unpublished; Alba and Chávez, 1974; Cameron and Cameron, 1976. West Texas - as summarized in McDowell, 1979.

tal. This close association of favored host rock and ore does not demonstrate either closely similar age or related origin, although both are possible. For example, at Tayoltita, the leading gold mine of Mexico in recent years, the host volcanic rocks belong to a thick section of andesites and rhyolites that was invaded by batholithic plutons about 45 m.y. ago, yet the veins were deposited about 40 m.y. ago, as indicated by the K-Ar age of feldspar in the gangue (Henry, 1975). In the Libertad-Ventanas district about 40 km south of Tayoltita, silver was produced in the past from veins in older volcanic rocks, but current production is from a vein in rhyolite ignimbrite of the upper volcanic supergroup (Albinson, personal communication). Precious metal deposits in the Ocampo-Moris region of western Chihuahua occur chiefly in the lower volcanic rocks, yet their distribution appears to be related to younger structural features produced when the large mid-Tertiary caldera was formed (Bockoven, in progress). Thus, although the association of mineral deposits with the lower volcanic complex is strong, a successful exploration strategy might be based on mapping caldera structures within the upper volcanic supergroup of the Sierra Madre Occidental.

SYNTHESIS AND PLATE TECTONIC RELATIONSHIPS

At the time of origin of the igneous rocks of the Sierra Madre Occidental, Baja California was joined to the mainland of Mexico. Closing the Sea of Cortés places the Peninsular Ranges batholith adjacent to and west of the Sinaloa batholith. Magmatism in the western half of the Peninsular Ranges batholith appears to have been continuous and relatively static for 30 m.y. prior to 105 m.y. ago (Silver, 1979). At that time plutonic activity shifted progressively eastward across Sonora (Silver, 1979; Anderson and Silver, 1974) and across Sinaloa (Henry, 1975). Also in early to middle Cretaceous time andesitic volcanism spread far inland reaching into southern Arizona and southeastern New Mexico (Hayes, 1970), and across Sonora into western Chihuahua (de Cserna, 1970). As far east as the Majalca area north of Chihuahua City (Figure 1), two sets of deformed older volcanic rocks lie beneath horizontal Eocene ash flows (Mauger, 1977; Spruill, 1977). Volcanism again reached into southeastern Arizona, Chihuahua and Durango in Late Cretaceous-earliest Tertiary time (Hayes, 1970; McDowell and Keizer, 1977), while plutonism seems to have progressed steadily eastward until about 45 m.y. ago, then to have come to an almost complete halt throughout the coastal region and the Sierra Madre Occidental. Major volumes of igneous activity with ages between 45 and 35 m.y. are unknown southwest of a line through Chihuahua City and Durango City.

It has been suggested that the Peninsular Ranges batholith and associated volcanic rocks were formed in an island arc that later collided with the continent (Gastil *et al.*, 1978). Large bodies of reef limestone occur in the midst of volcanic rocks and volcaniclastic sediments in northwestern Baja California, in northern Sinaloa, in southern Mexico near Colima (Bonneau, 1976), and on the coast of Sinaloa near Mazatlán. Northwest of Mazatlán occurs a belt of mafic and ultramafic rock, and at the north side of Mazatlán thinly layered siliceous sediments (recrystallized chert beds ?) show evidence of contemporaneous deformation. Farther east the plutonic rocks and associated volcanic rocks are largely covered. Scattered exposures of the lower volcanic complex east of the Sierra Madre Occidental in Durango and central Chihuahua generally disclose andesitic rocks associated with platform limestone formations of Cretaceous age.

It may be postulated that in early Cretaceous time the southwestern margin of the North American craton extended through western Sonora and beneath the central part of the Sierra Madre Occidental and western part of the Trans-Mexican volcanic belt. West of this hypothetical line, the present cratonic rocks appear to be dominantly Mesozoic batholithic plutons and associated volcanic and clastic rocks. It is unlikely that all of these rocks are part of a simple island arc, and Rangin (1978) has suggested the existence of a microcontinent with some older rocks in his paleogeographic reconstruction for this region.

A high level of magmatic activity returned to the Sierra Madre Occidental in spectacular fashion about 34 m.y. ago. Topography developed during the previous 10 m.y. was quickly buried beneath successive widespread ignimbrite flows. During the period from 34 to 27 m.y. ago unmatched quantities of rhyolitic igneous rock were emplaced not only in the Sierra Madre Occidental but also across much of eastern Chihuahua and Trans-Pecos Texas. No other interval of the past 100 m.y. has a comparable volume and wide distribution of similar volcanic activity. About 27 m.y. ago magmatism in the Sierra Madre Occidental gradually declined once again. After 23 m.y. ago major volcanism was occurring only to the east in west Texas and to the west near the present-day Sea of Cortés.

Aside from curvilinear normal faults associated with formation of calderas, regional faulting appears to be entirely younger than emplacement of the upper volcanic supergroup. Minor alkali basalts of Miocene age near Durango have been found in association with Basin-Range style faulting.

The igneous history of western Mexico generally accords with global tectonic patterns emerging from sea-floor spreading studies. The geologic record indicates plate convergence during emplacement of the lower volcanic complex, though this cannot be confirmed in the marine geology of the Pacific. However, a global reorganization of plates 80 m.y. ago, cited by Coney (1972) as initiating the Laramide orogeny in western North America, was not reflected in the pattern of magmatism of the lower volcanic complex. The general calc-alkaline and dominantly intermediate chemistry of the lower volcanic complex is typical for an island-arc or continental-margin setting.

The abrupt decline in magmatism 45 m.y. ago, along with the end of early Tertiary tectonism in western Mexico, do coincide approximately with a global reorientation of plate motions 40 m.y. ago (Coney, 1972). Another manifestation of this event is the elbow of the Hawaiian-Emperor seamount chain, caused by a change in absolute motion of the Pacific plate 42 m.y. ago (Dalrymple and Clague, 1976). Interaction between the Farallon and North America plates produced a minimum of continental margin magmatism in the Sierra Madre Occidental between 45 and 34 m.y. ago. The nature of this interaction may have been a pause or decline in the rate of plate convergence and/or a related change in dip of the subducted slab. Another possibility is the subduction of a hypothetical active ridge, once located east of the present East Pacific Rise, for which all evidence has now been destroyed. Subduction of young oceanic lithosphere flanking a ridge can result in diminished magmatism (DeLong and Fox, 1977). Careful study of the subduction related magmatic history of the region may distinguish between these alternatives.

The period of decreased magmatism ended 34 m.y. ago with a great outburst of ignimbrites and related rocks along the entire Sierra Madre, one of the most intense magmatotectonic events recorded on the earth. Some characteristics of these rocks defy easy correlation with plate tectonic history. Though calc-alkalic in composition, they are distinctly bimodal in SiO_2 content. Available age data indicate that much of the enormous volume was emplaced in a brief span of 7 m.y., between 34 and 27 m.y. ago (Figure 4). These features are not typical of continental margin sequences and suggest association with a single event rather than a prolonged subduction interval.

At least for the time from magnetic anomaly 13 (38 m.y.) to the present, the marine geology of the eastern Pacific contains a detailed plate tectonic history for comparison with events at the adjacent continental margin (Atwater, 1970; Handschumacher, 1976). Although the upper volcanic supergroup was emplaced during a period of Farallon-North America plate convergence, nothing in the sea-floor record accounts for the onset of major rhyolitic volcanism 34 m.y. ago. The termination of this magmatism, however, can be readily linked to cessation of subduction associated with collision of the east Pacific spreading system and the North American continental margin. This began 29 m.y. ago (Atwater, 1970), producing a lengthening transform margin, as two triple junctions migrated apart. Analysis of magnetic anomaly patterns along a major arc segment of the east Pacific spreading system indicates that a major reorientation occurred 26 m.y. ago (Handschumacher, 1976). This appears to be an important regional consequence of the encounter of the Pacific and North American plates. It coincides well with our evidence that magmatic activity slackened in the Sierra Madre Occidental about 27 m.y. ago. Continued subduction of remnants of the Farallon plate probably accounts for diminished activity in the western Sierra, and Miocene volcanism adjacent to the Sea of Cortés (Gastil *et al.*, 1979), and in southern Mexico and Central America (McDowell, unpublished; McBirney *et al.*, 1974).

In plate-tectonic reconstructions of Central America it is generally recognized that the Chortiz block, on which Honduras is located, has reached its present position by moving eastward relative to southern Mexico. During Cretaceous time this block was located in the Pacific southwest of Mexico and underwent considerable movement and rotation as a microcontinent (Gose and Schwartz, 1977). It is possible that by Late Cretaceous or early Tertiary time it had been joined to the southern margin of Mexico and that the mid-Tertiary volcanic rocks of Central America are a southeastern extension of the Sierra Madre Occidental. It is significant that the oldest ignimbritic volcanism in Central America occurred about 30 m.y. ago (McBirney *et al.*, 1974; McDowell, unpublished).

It is uncertain how far inland igneous activity can be attributed to continental-margin tectonics. Barker (1977) argued that the alkalic rocks of Trans-Pecos Texas are related to mantle diapirism and associated crustal rifting. They overlap in timing with the upper volcanic supergroup, but major activity in Trans-Pecos Texas occupied a longer span from 45 to 20 m.y. ago (Figure 4). Between these two provinces lies a less well defined belt of volcanic rocks of intermediate alkalinity in eastern Chihuahua and westernmost Texas. Age distribution for these rocks is likewise intermediate; a peak of activity coincides with that for the upper volcanic supergroup, but the span of activity is much longer (Figure 4). The earliest volcanism in eastern Chihuahua and in Trans-Pecos Texas occurred while magmatic activity was minimal in the Sierra Madre Occidental.

If the mantle diapirism beneath west Texas was itself related to plate convergence, then origin as a consequence of subduction may be suggested for all of these Tertiary volcanic rocks. The increase in alkalinity inland fits well with this hypothesis. However, the earlier onset of volcanism in eastern Chihuahua and west Texas, and the episodic timing and bimodal composition of the upper volcanic supergroup pose significant problems.

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