LATE CENOZOIC VOLCANISM AND METALLOGENESIS OVER AN ACTIVE BENIOFF ZONE IN CHIAPAS, MEXICO [1]

by

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Abstract

Chiapas, Mexico is a critical area for plate tectonic phenomena. The southeast part of the state, in the region of Motozintla, marks the juncture of three plates: the American, Cocos, and Caribbean plates. The Central (Middle) American trench strikes parallel to the coastline and to most of the large-scale geological features of Chiapas such as the Sierra Madre de Chiapas, the Central Depression, and the folded ridge and valley province of northeastern Chiapas.

The offshore trench and inland Chiapas are regions of intense seismicity. There is a distinct tendency for fewer but deeper and more intense earthquakes proceeding from the trench to inland Chiapas. This pattern of seismicity is similar to that of other Benioff zones and demonstrates that the Cocos plate is continuing to subduct under Chiapas.

The major mineral deposits of Chiapas are genetically associated with Cenozoic plutons. One set of plutons has been shown by K-Ar dating to be middle to late Miocene in age. These plutons intrude an ancient Paleozoic batholithic terrain within the Chiapas Massif. This set of plutons lies along an abandoned segment of the Miocene Central American-Mexican volcanic arcs.

The second set of plutons is clearly associated with a belt of calc-alkalic, andesitic to dacitic stratovolcanos of Pliocene and Pleistocene age. The volcano El Chichón in that belt contains an active solfatara field. Others still retain much of their primary structure. This belt is referred to as the modern Chiapanecan volcanic arc.

The rate of erosion required to expose the mineral deposits below the tops of the stratovolcanos, according to the model of Sillitoe (1973), is from 300 m/m.y. to 900 m/m.y.

Prior to 9 m.y. ago, the ancestral Mexican volcanic arc was probably continuous to Cape Corrientes. Between 9 and 3 m.y. ago, reorganization of the subducting Cocos plate resulted in a volcanic arc, which is convex to the north. A magma gap exists within the Central Depression of Chiapas.

We conclude that continuing ore genesis in Chiapas is associated with subduction of the Cocos plate. The ore deposits are the roots of calc-alkalic stratovolcanos. Both the ancestral Miocene Central American-Mexican arcs and the modern arc are prime targets for ore deposits of Neogene age.

Plate Tectonic Setting of Chiapas

This work is part of a cooperative investigation of the age and genesis of the Mesozoic-Cenozoic metallogenetic provinces of the Republic of Mexico by the Consejo de Recursos Minerales and the Laboratory of Isotope Geochemistry of The University of Arizona. Most of the field work was done during the winters of 1974 and 1975. Chiapas was selected for an early phase of the investigation because of its unique plate tectonic setting (Fig. 1). It is located near the junction of three plates:

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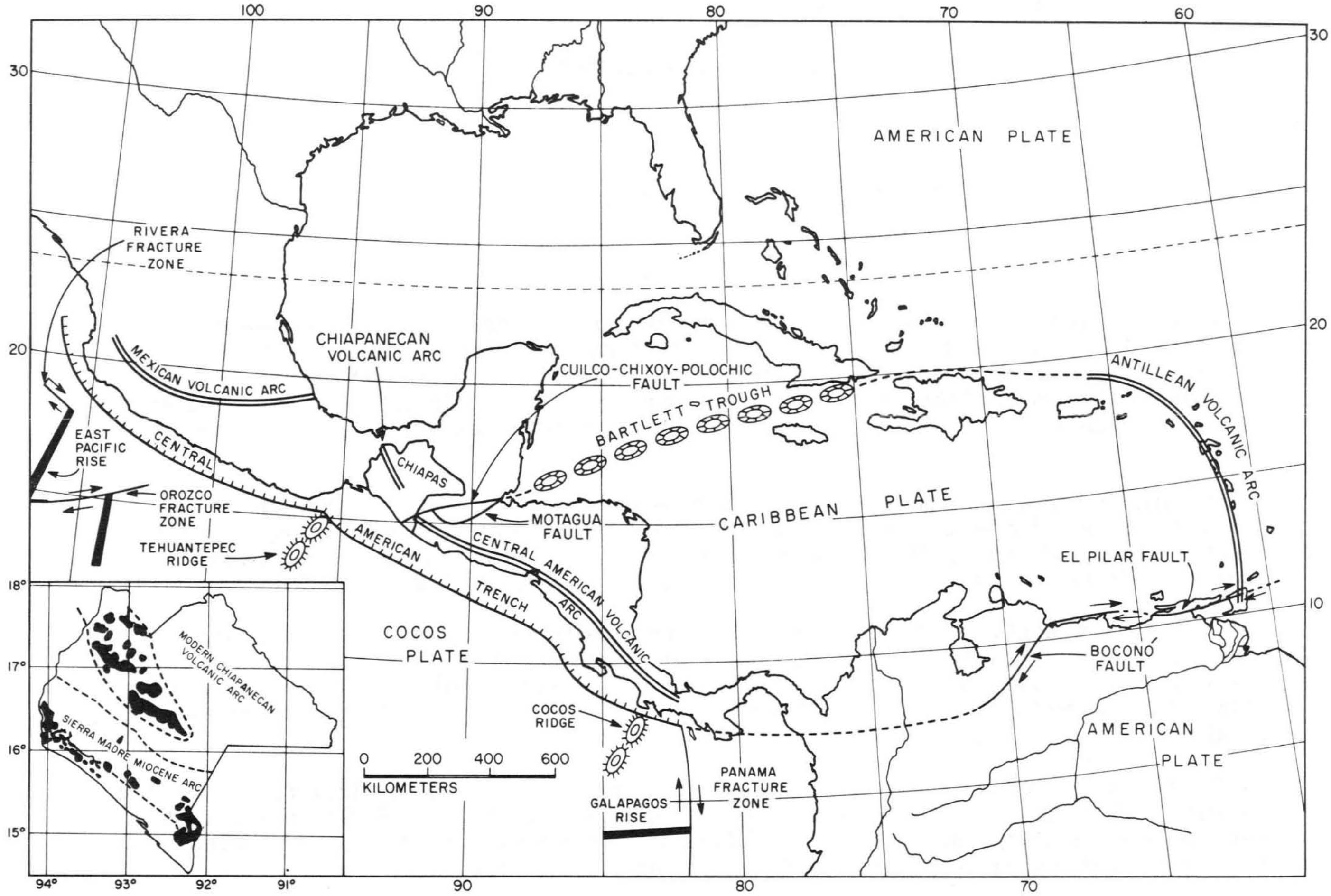

Fig. 1. Plate tectonic sketch map of the Cocos, Caribbean, and American plates from Cape Corrientes to Venezuela. Data for this figure was obtained from Chase, Menard, and Mammerick (1970), Fisher (1961), Herron (1972), Molnar and Sykes (1969), Muehlberger and Ritchie (1975), Schubert and Sifontes (1970), Schubert (1974), and Shor and Fisher (1961).

the American, the Caribbean, and the Cocos plates. The Cuilco-Chixoy-Polochic fault forms the present boundary between the Caribbean and American plates in southeastern Chiapas and Guatemala (Kesler, 1971; Muehlberger and Ritchie, 1975). The Central (Middle) American trench forms the boundary between these plates and the Cocos plate roughly paralleling the Central American shoreline.

The offshore trench and inland Chiapas are regions of intense seismicity (Fig. 2). There is a distinct tendency for fewer but deeper and more intense earthquakes proceeding from the trench to inland Chiapas. This pattern of seismicity is similar to that of other Benioff zones and demonstrates that the Cocos plate is continuing to subduct under Chiapas.

Physiographic Provinces of Chiapas

Chiapas can be divided for convenience into seven physiographic provinces (Fig. 3): Province 1 consists of the Pacific coastal plain. Province 2 is the Sierra Madre del Sur of Chiapas, which will be referred to as the Chiapas Massif. Province 3 is the Central Depression, a grabenlike depression through which the Río Grijalva flows. Province 4 comprises the high plains surrounding San Cristóbal de las Casas. Province 5 is a valley and ridge province, which decreases in elevation to the northeast as the basin of the Río Usumacinta is approached. Province 6 is the northern mountain province. The eastern part of this province contains northwest-trending valleys and ridges which are a continuation of the less rugged valley and ridge region within Province 5. The folded sedimentary rocks in the western part of Province 6 have been disrupted by the differential vertical tectonics resulting from igneous intrusions and the presence of stratovolcanos. Province 7 is part of the Gulf of Mexico coastal plain.

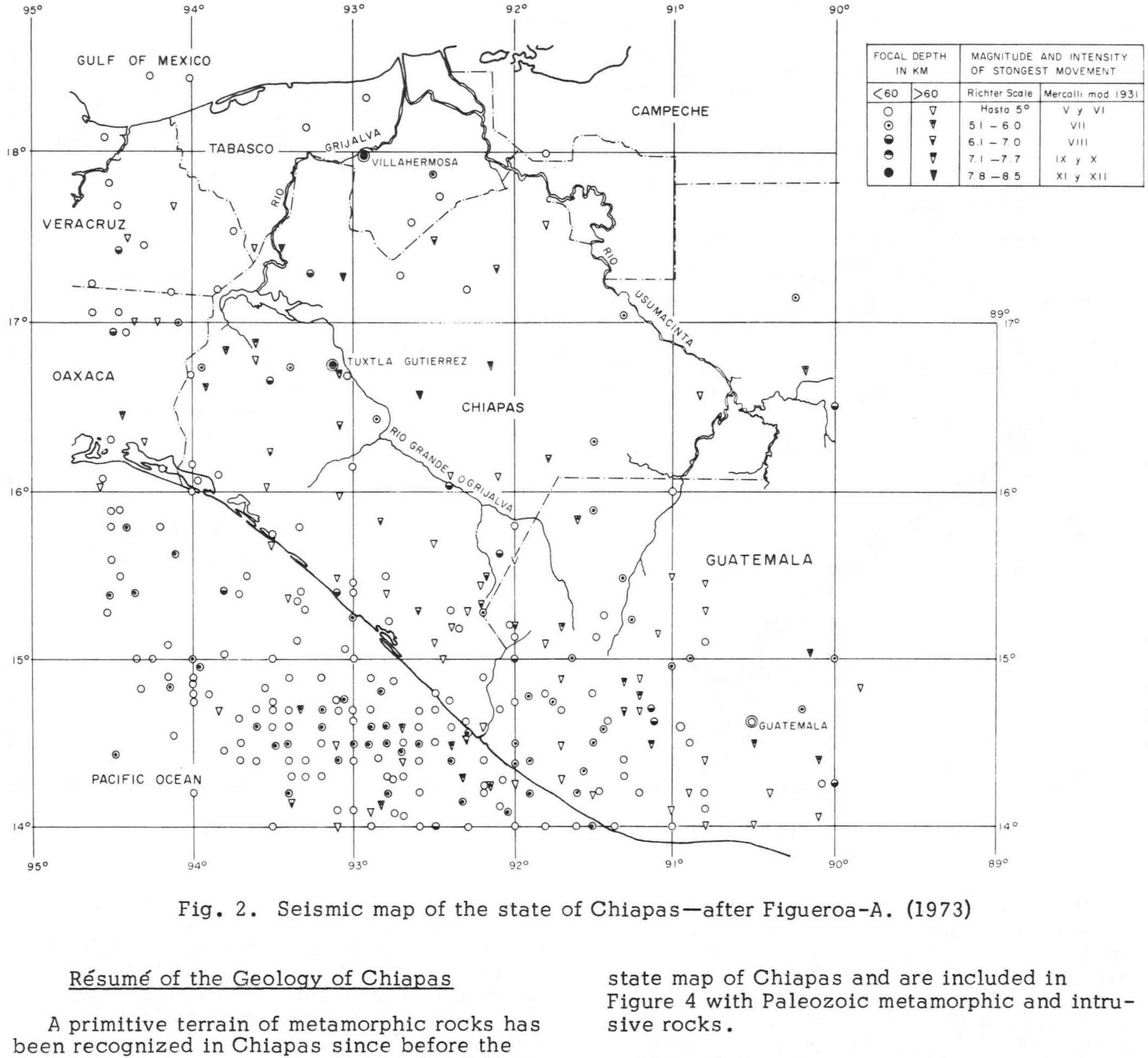

Fig. 2. Seismic map of the state of Chiapas—after Figueroa-A. (1973)

Résumé of the Geology of Chiapas

A primitive terrain of metamorphic rocks has been recognized in Chiapas since before the end of the 19th century (Aguilera and Ordóñez, 1893). More recently, Pantoja-Alor and others (1974) have demonstrated that at least some of these metamorphic rocks within the Sierra Madre del Sur of Chiapas (Province 2, Fig. 3) are late Precambrian in age approximately correlative with the Oaxaqueña orogeny of Fries, Schmitter, Damon, and Livingston (1962). This orogenic belt extends in an arc from Guatemala through southwestern Chiapas, central Oaxaca, northeastern Guerrero, Puebla, and Hidalgo to western Tamaulipas (Fries, Schmitter, Damon, Livingston, and Erickson, 1962; Fries and others, 1974). Fries, Schmitter, Damon, and Livingston (1962) correlate the Oaxaqueña orogeny with the Grenville orogeny in Canada. These rocks have not been differentiated from later metamorphic rocks on the state map of Chiapas and are included in Figure 4 with Paleozoic metamorphic and intrusive rocks.

These Paleozoic igneous intrusions and metamorphic rocks range in age from Cambrian through Permian (Damon and Salas, 1975). In the Sierra Madre del Sur of Chiapas, the final event of the Paleozoic was the intrusion of a late Permian batholithic complex, which intrudes the older metamorphic rocks and the Santa Rosa Formation of Permian age.

The Santa Rosa Formation consists predominantly of limestones and dolomites with intercalated carbonaceous beds. These beds were deposited in the Paleozoic Guatemalan geosyncline, which forms a great arc from northeast to northwest, convex toward the south. This geosyncline crossed Belize, much of Guatemala, and virtually all of Chiapas.

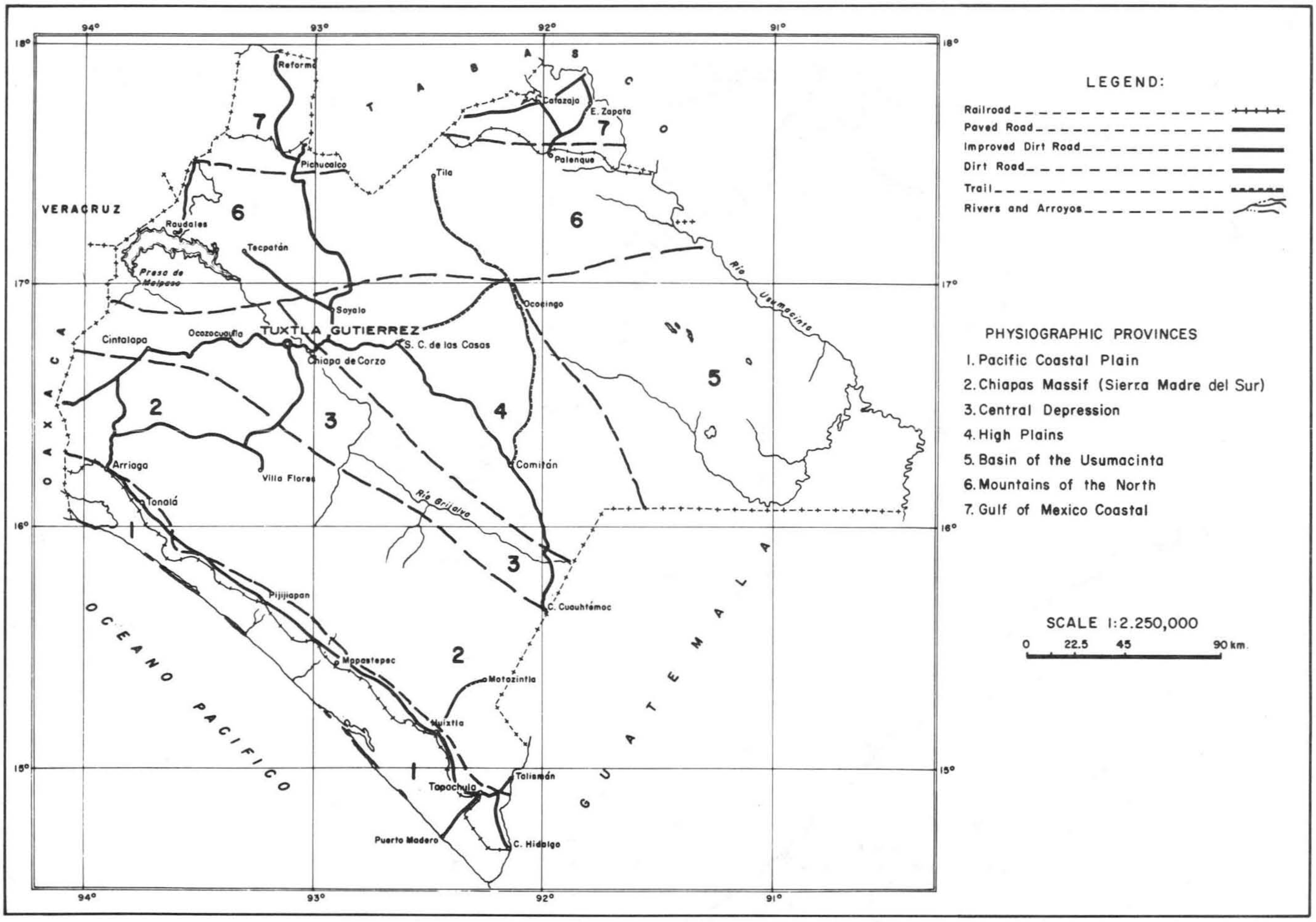

Fig. 3. The physiographic provinces of Chiapas—after Böse (1905)

Following the deposition of sediments in the Guatemalan geosyncline, a large basin was the locus of salt deposition, the so-called Isthmus Salt Basin of Late Jurassic age or post-Callovian–pre-late Oxfordian according to Viniegra-O. (1971). This salt basin occupied most of Chiapas excepting the Sierra Madre del Sur and Pacific coastal plain. In northern Chiapas, salt deposition continued into latest Jurassic (Kimmeridgian-Tithonian) time according to Viniegra-O. (1971). The salt deposits are overlain toward the Chiapas Massif by the red beds (Lechos Rojos) of the Todos Santos Formation. On the state geologic map of Chiapas (Fig. 4), the Todos Santos Formation is referred to as Triassic-Jurassic in age; however, according to Viniegra-O. (1971), this formation must be Late Jurassic and Early Cretaceous in age. Some geologists refer to the Early Cretaceous continental red beds intertongued with marine limestones as the San Ricardo Formation (Richards, 1963). We examined the Todos Santos red beds east of Cintalapa. The formation there consists of aeolian cross-bedded sandstones and cobble conglomerates containing quartz, granitic debris, and abundant volcanic rock grains and cobbles. In one place, we found a cobble of red-bed sandstone within a Todos Santos red-bed conglomerate. The general aspect was that of debris from the unroofing of the ancestral Chiapas Massif (Province 2, Fig. 3). The abundance of volcanic rock fragments indicates that erosion of the Chiapas Massif had not proceeded to a great depth at the time of deposition of the Todos Santos Formation. From the outcrop pattern (Fig. 4) one can surmise that debris from unroofing of the massif was distributed to a basin lying to the northeast.

Marine conditions prevailed throughout Chiapas following the deposition of the San Ricardo Formation. Limestone and dolomites are most abundant with lesser amounts of chert, shale, and sandstone. Occasionally, deposition of marine sediments was interrupted by formation of soils, some of which were lateritic. During this time, Chiapas was part of the Mexican geosyncline (Kay, 1951).

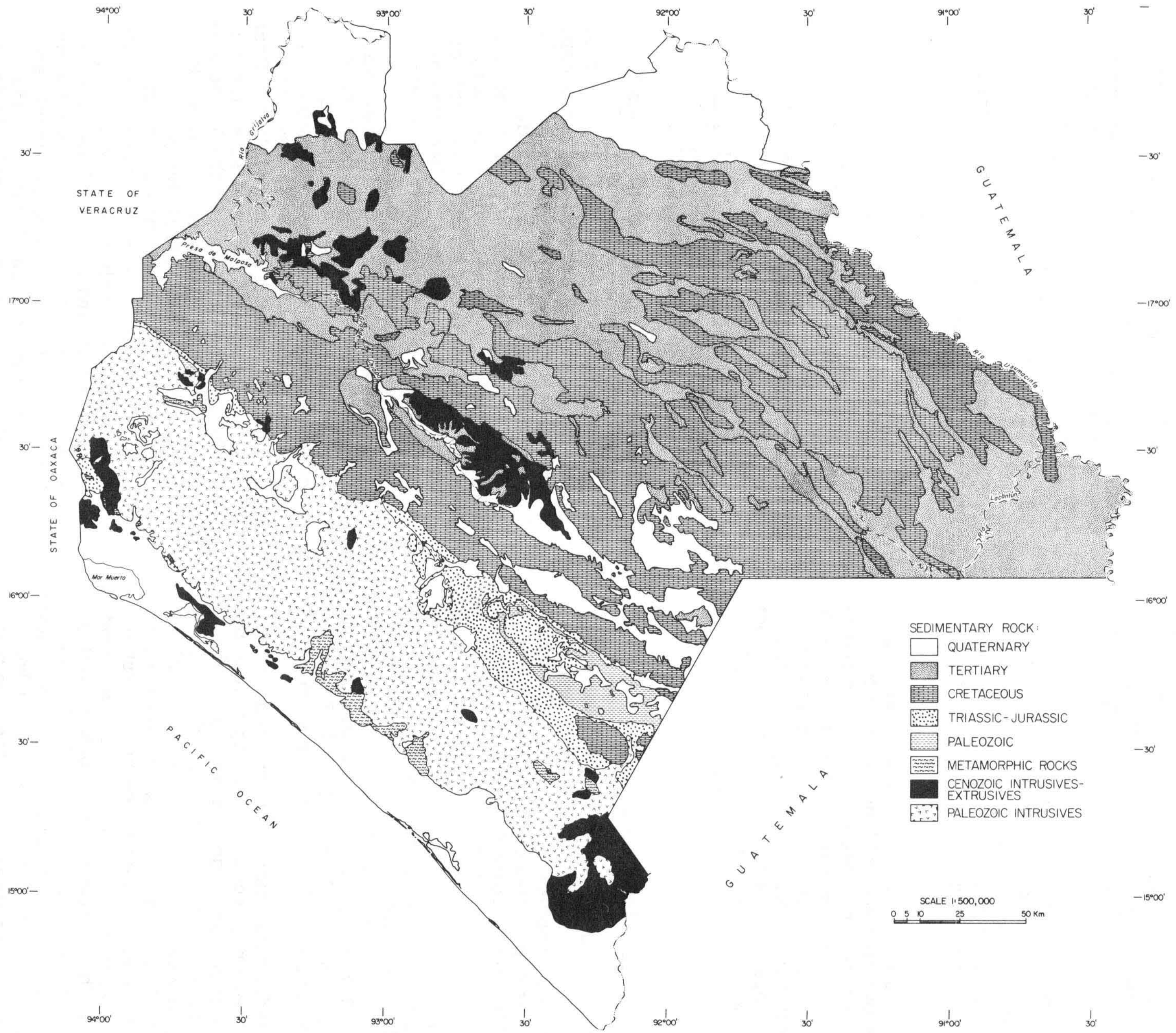

Fig. 4. A simplified geologic map of Chiapas compiled from Petroleos Mexicanos and Consejo de Recursos Minerales sources

During the early Cenozoic, marine deposition retreated to the northeast. By late Eocene time, the southwestern half of Chiapas was a land area and streams were carrying cobbles of schist, granite, and quartzite to the northeast beyond what is now the Central Depression of Chiapas (Province 3, Fig. 3). These streams deposited the conglomerates that are included within the El Bosque Formation.

Marine conditions prevailed in northern Chiapas through the Oligocene epoch. However, the seas gradually retreated to the north toward the Gulf of Mexico. Terrestrial conditions prevailed from Miocene time to the present.

The state geologic map of Chiapas (Fig. 4) shows two episodes of igneous activity: an early Cenozoic episode of dioritic, granodioritic, and quartz monzonitic intrusions and a late Cenozoic episode of volcanic activity. We will demonstrate in this paper that there are two episodes of igneous activity, but both are Neogene in age rather than separated into Paleogene intrusive and Neogene volcanic episodes.

K-Ar Dating Techniques

The K-Ar dating method requires precise, accurate determinations of K and ^{40}Ar (Dalrymple and Lanphere, 1969). In the Laboratory of Isotope Geochemistry, K was determined by atomic absorption spectrophotometry. The solution used contained 0.1 g of the sample as sulfate in 200 ml of aqueous solution containing 800 ppm Li and 1000 ppm Na. Two aliquots were measured for each sample. The atomic absorption spectrometer used was a Perkin-Elmer 403, single beam instrument. A 30 lb-60 lb acetylene-air flame was used with the wavelength dial set at 3827 Å (3-slot burner head in parallel position, slit 4, filter in).

Molybdenum crucibles were used for the radio frequency induction heating to fuse the sample to release argon for analysis. The molybdenum crucible was suspended by a platinum wire and carefully centered within a 90-mm air-cooled pyrex fusion envelope. Four samples were mounted in the fusion system, and the system was baked over the weekend at 270°C. The system was also baked overnight after every fusion. In addition to the usual titanium foil gettering and conversion of hydrogen to water over CuO, a Zr-Al appendage pump provided a final purification step that insures very pure argon for mass spectrometric analysis.

Argon isotopes were analyzed on either a Nier-type 15.2 cm radius, 60° sector field mass spectrometer with magnetic sweeping or an MS-10, 5.1 cm, 180° mass spectrometer with electrostatic sweeping. Two analyses per fusion were made in the static mode.

For young samples, for example, samples of Pleistocene age, the standard error was determined primarily by the atmospheric argon contamination. The standard deviation for a sample with negligible air argon is 2.3%, 15% with 90% air argon, and 100% with 98.4% air argon.

All dates were calculated with the following decay constants:

$$\lambda_e = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$$

$$\lambda_\beta = 4.963 \times 10^{-10}\ \mathrm{yr}^{-1}$$

$$\lambda = 5.544 \times 10^{-10}\ \mathrm{yr}^{-1}$$

$$^{40}\mathrm{K/K} = 1.167 \times 10^{-4}\ \text{atomic ratio}$$

Age and Genesis of Cenozoic Igneous Rocks in Chiapas, Including the Southern Oaxaca Border Region

There are two regions within Chiapas that contain Cenozoic igneous rocks (see Fig. 4 and lower left-hand inset in Fig. 1). The first region lies in central and northwestern Chiapas (within physiographic Provinces 4, 6, and 7). The geologic map of Chiapas classifies the outcrops as early Cenozoic intrusive and late Cenozoic volcanic rocks. Before beginning field work in that area, we spent several days doing aerial reconnaissance. It became apparent from the morphology of the volcanic rocks as seen from low aerial altitudes that the region included domes, necks, and stratovolcanoes of no great antiquity. In fact, we were quite surprised to fly over a volcano, Volcán El Chichón, which had numerous active fumeroles. Volcán El Chichón is also known locally as Volcán de la Unión and Volcán Ostuacán. It is listed as the site of an active solfatara field in the Catalogue of the Active Volcanos of the World (International Volcanological Association, 1951-1973), but apparently it is not well known in Mexico as an active volcano. At a later date we ascended the volcano, which was thickly covered with jungle growth, necessitating the use of machetes to clear a path. The volcano has a central dome, which rises to 1,350 m above sea level, and a surrounding moat at an elevation of 950 m. The flanks are composed of hornblende dacite with a few quartz phenocrysts and disseminated pyrite. Both the moat and the dome are sites of active solfataric activity, which rises some 50 m into the air as extremely hot jets.

Table 1. Plio-Pleistocene K-Ar dates for the Chiapanecan volcanic arc

Sample no.	Material dated, description, and location	K-Ar age and 2 σ error m.y.
1	Whole rock, basaltic-andesite dike, strike N 30° W, dip approx. vertical, Arroyo La Danta, Minas Santa Fe, lat 17°20'24" N, long 93°02'40" W	2.79 ± 0.08
2	Biotite dike in Oligocene shale, strike N 66° W, dip approx. vertical, left bank of Río Ixhuatán between Río Cacate and Río Robajicara, Santa Fe area, lat 17°18'10" N, long 93°02' 18" W	2.29 ± 0.07
3	Biotite, diorite containing pyrite, bornite, and chalcopyrite, intruded into Oligocene limestone which has been converted to wollastonite, 450 m N of La Victoria Mina (Pb-Ag) beside Río Beneficio, near Highway 195, lat 17°22' N, long 93°02' W	2.29 ± 0.10
4	Biotite, unaltered, granodiorite dike in argillic alteration zone, contains disseminated pyrite, La Vuelta de Mico, 1.5 km from Minas Santa Fe on road from Beneficio, lat 17°22'12" N, long 93°02'16" W	2.24 ± 0.08
5	Whole rock, andesite, tilted and underlying pumiceous ash flow, Selva Negra between Rayón and Rincón Chamula on Highway 195 to Pichucalco near km marker 102, Santa Fe area, lat 17°10'18" N, long 92°58'45" W	2.17 ± 0.04
6	Whole rock, augite andesite with disseminated pyrite, Cerro Tzontehuitz, approx. 150 m below microwave tower, lat 16°47'14" N, long 92°36'01" W	2.14 ± 0.04
7	Whole rock, hornblende dacite, from volcanic complex composed of dacitic tuff, lahars, and hornblende andesites, 50 m below microwave tower at 2,800 m elevation, lat 16°47'30" N, long 92°36'01" W	1.95 ± 0.04
8	Hornblende, andesite, from hillside on W side of village of Zinacantán, approx. 2 km N of Pan American Highway, lat 16°44'36" N, long 92°42'36" W	0.850 ± 0.030
9	Hornblende, dacite from Cerro Lanza which is a volcanic rock with vertical flow banding, NNW of Nicolás Ruiz, lat 16°27'16" N, long 92°35'27" W	0.846 ± 0.024
10	Hornblende, dacite on Pan American Highway near village of Navenchuac about 11 km W of San Cristóbal de las Casas, lat 16°43'57" N, long 93°45'12" W	0.432 ± 0.029
12	Whole rock, dacite at 950 m altitude from Volcán de la Unión which was active in winter of 1974 with fumaroles associated with the central dome, near Colonia del Volcán, Santa Fe area, lat 17°24'35" N, long 93°15'10" W	0.209 ± 0.019

The moat is filled with charred logs, and the ground is hot to the touch. The dacite within the moat has suffered argillic alteration and pyritization as well as oxidation to yellow and red ochre. A white sublimate forms around the fumeroles and occasionally native sulfur is present. The dacite yielded a late Pleistocene age (sample 12, Table 1).

Table 1 (see also location map, Fig. 5) includes all of the K-Ar dates we have obtained for this region, which we refer to as the modern Chiapanecan volcanic arc. The oldest dates (2.17 to 2.79 m.y. or latest Pliocene in age (samples 1-5), are for volcanic and intrusive rocks of the Santa Fe mining district-Selva Negra region. Cerro Tzontehuitz, which is an impressive stratovolcano near San Cristóbal de las Casas, is also latest Pliocene in age (approximately 2 m.y., samples 6, 7). Other andesitic and dacitic volcanic fields of that area near the Pan American

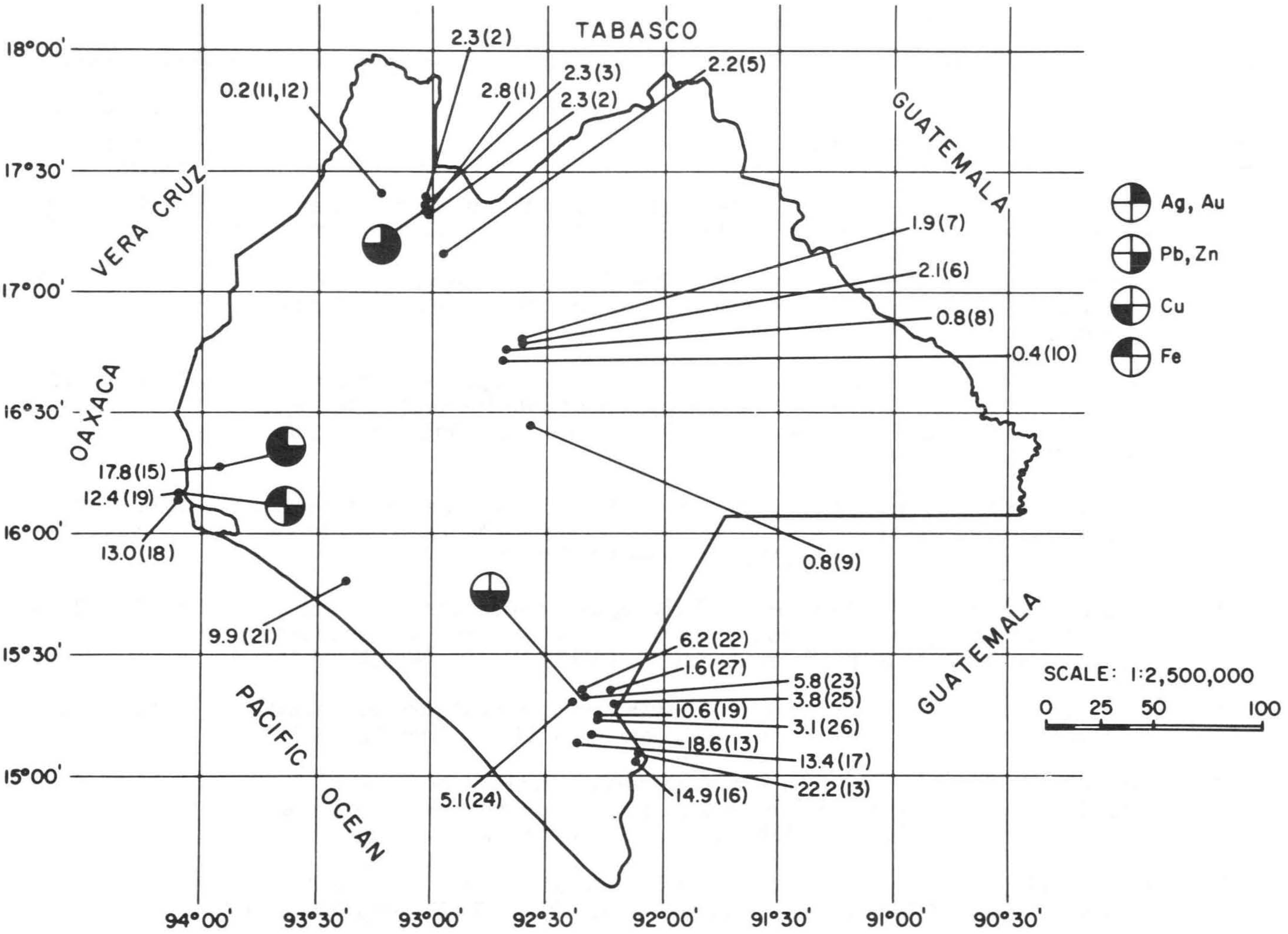

Fig. 5. Location map for samples and mineral deposits given in Tables 1-3 and discussed in text

International Highway in the general vicinity of San Cristóbal de las Casas yielded middle to late Pleistocene K-Ar dates (samples 8, 10). A volcanic plug near Nicolás Ruiz, with conspicuous vertical banding and the appearance of a Pelean spine, also yielded a middle Pleistocene age (sample 9). Thus it is apparent that the modern Chiapanecan volcanic arc is the locus of volcanic activity from at least latest Pliocene time (2.8 m.y. B.P.) to the present.

The second region of Cenozoic igneous activity lies within the Chiapas Massif and the Pacific coastal plain (Figs. 1, 4, 5). We refer to this as the Miocene Sierra Madre volcanic arc. K-Ar dates for this area are given in Table 2. Except for the Motozintla area in the vicinity of the Polochic fault (Fig. 1) where there is a large Pliocene stock cropping out over an area of about 70 km^2, the granodiorite, quartz monzonitic, and granitic stocks within this belt are early to late Miocene in age. The Motozintla stock is latest Miocene or earliest Pliocene in age (approximately 5.5 m.y.).

The geologic map of Chiapas (Fig. 4) includes a large volcanic area in the southeast corner of the state. Actually over much of this area, the volcanic cover has been removed exposing a granitic batholithic complex of Miocene age (10.6 to 22.2 m.y., samples 13, 14, 16, 17, 20). Volcanic rocks other than from the modern, majestic stratovolcano, Tacaná, do crop out in the area. For example, Cerro Boquerón, which is the remnant of an andesitic volcano, dates 3.13 m.y. (sample 26). The unwelded Pleistocene tuff near Motozintla contained fresh hornblende which yielded an early Pleistocene date (1.62 m.y., sample 27). The outcrop is weathered, which made identification of its mode of transport difficult, but it has aspects of an ash flow. Its source is not known, but most probably it originated to the east toward Guatemala.

The distribution of volcanic and subvolcanic rocks in Chiapas suggests that there has been a radical change in the geometry of the subducting Cocos plate between the time of emplacement of the plutons and volcanic rocks of the Miocene Sierra Madre arc in Chiapas and the emplacement of the stratovolcanos and related plutons in the modern Chiapanecan volcanic arc (Fig. 1, insert). This reorganization appears to have occurred between the time of the emplacement of the Miocene stocks and the extrusion of volcanics in the Santa Fe mining district, that is, between about 9 and 3 m.y. ago. The Pleistocene volcanism in southeastern Chiapas seems to be associated with the Central American arc on the Caribbean plate side of the Cuilco-Chixoy-Polochic fault rather than with the American plate.

It is interesting that the earthquake hypocenters associated with the subducting Cocos plate are anomalously shallow from about Mexico City southeast to the Isthmus of Tehuantepec, distances being measured perpendicular to the Central American trench (Molnar and Sykes, 1969). Southeast of the Isthmus of Tehuantepec, the hypocenters rapidly deepen moving inland from the trench. The volcanic axis follows a similar pattern moving inland southeast to the Isthmus of Tehuantepec and then moving closer to the Pacific Ocean southeast of the Isthmus of Tehuantepec. Within the Caribbean plate, the Central American volcanic arc fairly closely parallels the Pacific Coast and the Central American trench. The modern Chiapanecan volcanic arc represents the volcanic arc returning to the coastal region. There is no gap in volcanism between the modern Chiapanecan volcanic arc and the Mexican volcanic arc; the apparent gap in Figure 1 is filled by a large volcanic center around San Andrés Tuxtla and an almost continuous volcanic outcrop to central Veracruz. There is, however, a real gap in Chiapas between the Chiapanecan and Central American arcs. We have searched for but have not found volcanic rocks within the Central Depression of Chiapas (Province 2, Fig. 3). The apparent gap to the northwest is an artifact of the manner of constructing Figure 1 in which the arc is made to pass through the center of volcanic outcrops.

The convex-to-the-north pattern of the Mexican-Chiapanecan volcanic arcs is probably the result of a bending of the subducting Cocos plate which steepens to the northwest and southeast and is very shallow in between the two segments of what is almost a continuous volcanic arc. Prior to about 9 m.y. ago the Central American arc continued to parallel the Pacific Coast and Central (Middle) American trench northwestward through Chiapas to Oaxaca and, quite probably, although evidence remains to be documented, through Guerrero, Michoacán, and Jalisco. The previous arc was active for at least 13 m.y., prior to the Pliocene epoch. It is interesting that this reorganization appears to be approximately correlative with events to the north. According to Larson (1972, p. 3345): "The Middle American Trench north of the Rivera Fracture Zone became nearly dormant as a plate boundary 8 to 10 m.y. ago when the rise crest changed from the Pacific-Farallon to the Pacific-Rivera plate boundary."

Relationship Between Volcanism and Metallogenesis in Chiapas

There are a number of significant mineral deposits within the Miocene Sierra Madre arc. The region of the Motozintla stock has been set aside by the Mexican Government as a mineral reserve. We examined a porphyritic outcrop at Tolimán (site of sample 23, Fig. 5) with disseminated sulfides and veins which appears to have all the aspects of a classic disseminated porphyry copper deposit. Within a mile of this outcrop, argillic and propylitic as well as potassic alteration can be observed. Under the hand lens, pyrite, bornite, chalcopyrite, and sphalerite were abundant and readily observable.

Cerro Colorado (sample 15 location, Fig. 5), which is only 100 m from the coastal railroad, also has the typical characteristics of a porphyry copper-limestone contact zone. The prospect occurs within a hill, which is capped by marble, silicified limestone, and magnetite. Malachite, azurite, sphalerite, galena, and asbestos were observed. What appeared in the field to be sericite was found in the laboratory to be almost pure paragonite, suggesting alteration by a hydrothermal convection system involving sea water.

We also collected from the La Carmen prospect in Oaxaca near the Chiapas border (sample locations 18, 19, Fig. 5). La Carmen is a contact metamorphic deposit of granodiorite in limestone. The most important mineral is magnetite. However, zinc blende (sphalerite) is very abundant. The limestone is converted to marble and wollastonite. We collected a sample of zinc ore with greenish books of mica about 1 cm in diameter. Much to our surprise, this mica also was shown to be paragonite in the laboratory, again suggesting that the coastal area was inundated by sea water in mid-Miocene time.

Much of the Chiapas Massif is most probably an excellent target for Miocene ore deposits associated with the roots of stratovolcanos. Most of the Chiapas Massif is quite inaccessible, and time did not permit a thorough reconnaissance. However, we examined stream gravels between the sampled outcrop (sample location 21, Fig. 5) and long 92°40' W. Volcanic and subvolcanic rocks are abundant in the cobbles in the rivers between those coordinates along the coastal highway.

There is one mining area within the modern Chiapanecan volcanic arc around Santa Fe (sample localities 1-4, Fig. 5). At Santa Fe there are large underground workings which were mined for gold by an English company just before the Revolution of 1910. A French firm mined gold in the area following the revolution. At the present time, Minera Corza has a lease on the property. There is abundant copper, zinc, silver, and lead mineralization as well as gold. Sulfide minerals are ubiquitous within a stock outcrop of 2,000-m radius. Mining continued at the La Victoria mine until 1972. The Santa Fe mine proper is a contact metamorphic deposit with granodiorite intruded into Oligocene limestones forming a pure-white wollastonite cap. Vein deposits have also been mined. Disseminated sulfides occur throughout most of the stock that we examined.

Unlike many Mexican states, there is little tradition of mining in Chiapas. Nevertheless, both the modern and Miocene arcs provide a fruitful field for exploration. The presence of stratovolcanos in all stages of dissection by erosion and the association of sulfide mineralization with the remnants is in conformity with the relationships suggested by Sillitoe (1973) between stratovolcanos and porphyry copper deposits as well as lead, zinc, and previous metal veins and replacements.

The rate of erosion required to erode stratovolcanos in the Motozintla area is not unreasonable. The majestic stratovolcano Tacaná rises from the Pacific coastal plain to an altitude of about 4,050 m. According to Sillitoe (1973), the tops of porphyry copper deposits begin at a depth of 1.5 to 3 km. The deposit at Tolimán (Motozintla stock) appears to be eroded below the top as defined by Sillitoe, but erosion would have to continue to a much greater depth, according to his model, to expose the bottom of the deposit at Tolimán. A reasonable estimate would be erosion to a depth of 4 ± 1 km in 6 m.y. or about 660 ± 170 m/m.y. At this rate, only 12 m.y. would be required to erode 8 km and reach the bottom of a porphyry copper system in the Motozintla area. In fact, we have dated a number of unmineralized granites in southeastern Chiapas at from 11 to 22 m.y. (samples 13, 14, 16, 17, 20 in Table 2), which is in good agreement with the time required to reach the bottom of porphyry copper systems. The amount of erosion in 3 m.y. would be about 2 km or insufficient to completely remove the volcanic apron around volcanos of that age. The preservation of andesites at Cerro Boquerón of 3 m.y. age is quite compatible with the postulated rate of erosion.

In the Santa Fe mining district and at Cerro Tzontehuitz, 2 m.y. has not been sufficient time to remove the volcanic apron. Erosion rates in the Arriaga area, which has a lower rainfall, must be less than 660 m/m.y. or the mineral deposits at Cerro Colorado and Mina La Carmen would have been destroyed by erosion. However, the erosion rate in the Arriaga district need not be less than 300 m/m.y.

It is unlikely, with this rate of erosion, that pre-Neogene porphyry-type deposits would be preserved within the Chiapas Massif. Consequently, the Permian batholith and old igneous rocks would not be expected to be likely prospects for porphyry-type deposits. However, the entire length of the Sierra Madre del Sur from Cape Corrientes to Guatemala is a likely target for Neogene porphyry-type deposits.

Conclusions

Two Neogene volcanic arcs can be defined within Chiapas. The Miocene Sierra Madre volcanic arc was abandoned between 9 and 3 m.y. ago when the modern Chiapanecan volcanic arc came into existence as a result of a reorganization of the subducting Cocos plate. Both Neogene volcanic arcs are the locus of mineral deposits associated with calc-alkalic stratovolcanos in accord with Sillitoe's (1973) model. The rate of erosion required to expose these mineral deposits is between 300 m/m.y. and 900 m/m.y.

The still-active modern Chiapanecan volcanic arc is essentially continuous with the Mexican volcanic arc (Mexican volcanic axis or Eje Volcánica). The ancestral Miocene volcanic arc was probably continuous with the Central American volcanic arc from the eastern extremity of the Panama fracture zone to Cape Corrientes.

Both the ancestral volcanic arc, which parallels the Pacific Coast and the Central American trench, and the modern Chiapanecan arc, which is convex to the north, are prime targets for Neogene ore deposits.

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This work would not have been possible without the constant support and encourage-

Table 2. Neogene dates for the Sierra Madre del Sur and coastal plain in Chiapas and neighboring Oaxaca

Sample no.	Material dated, description, and location	K-Ar age and 1 σ error m.y.
13	Biotite, biotite-hornblende granite, collected beside the Puente Monte Perla at 1 km on road from Tuxtla Chica to Unión Juárez, lat 15°03'04" N, long 92°05'47" W, Chiapas	22.2 ± 0.5
14	Biotite, granitic intrusion, 1 km S of Finca Santa Anita, Motozintla area, lat 15°08'46" N, long 92°20'25" W, Chiapas	18.7 ± 0.4
15	Whole rock, altered quartz monzonite with paragonite, epidote, and tourmaline, intruded into a cap of marbleized limestone; chalcopyrite, malachite, azurite, magnetite, and sphalerite within the contact zone; at Cerro Colorado, 100 m from coastal railroad, 5 km NW of Arriaga, lat 16°16'57" N, long 93°58'20" W, Chiapas	≦ 17.8 ± 2.6 (may contain significant amount of excess radiogenic argon)
16	Biotite, granitic intrusion on the flank of Volcán Tacaná, about 200 m E toward Juárez from the Finca Muxval, Unión Juárez area, lat 15°04'47" N, long 92°04'33" W, Chiapas	14.9 ± 0.3
17	Biotite, granitic intrusion with pyrite, Finca Chajul in Cerro Soconuscos, Motozintla area, lat 15°10'51" N, long 92°18'08" W, Chiapas	13.4 ± 0.3
18	Biotite, granodiorite, Arroyo de Mangos, SE of La Carmen mine, approx. 1 km from Pan American Highway, Tepanatepec area, lat 16°26'24" N, long 94°06'33" W, Oaxaca	13.0 ± 0.3
19	Biotite, granitic intrusion into Cretaceous limestone with zinc blende (sphalerite) and wollastonite in contact zone, samples in Arroyo between Cerro La Carmen and mineralized hill, about 500 m SW of Pan American Highway, Tepanatepec area, lat 16°26'31" N, long 94°06'32" W, Oaxaca	12.4 ± 0.3
20	Biotite, hornblende-biotite granite, on road from Cerro Boquerón to Berriozábel from Motozintla about 4 km from Niquivil junction, near Tzuma, Motozintla area, lat 15°16'38" N, long 92°17'01" W, Chiapas	10.6 ± 0.2
21	Biotite, granite outcrop along coastal highway at the Potrero de la Gringa, Finca Perseverencia, Tonolá area, lat 15°50'17' N, long 93°28'02" W, Chiapas	9.95 ± 0.27
22	Sericite, pyritized fanglomerate, Mina de Concepción, Motozintla area, lat 15°20'34" N, long 92°20'47" W, Chiapas	6.18 ± 0.13
23	Biotite, K-silicate altered quartz monzonite porphyry with pyrite, bornite, chalcopyrite, and sphalerite, below the bridge at Tolimán, Motozintla area, lat 15°19'08" N, long 92°19'50" W, Chiapas	5.75 ± 0.10
24	Biotite, granodiorite porphyry intruded into the metamorphic complex of the Rancho Campeche area, km 27.5 on road from Belizario Domínguez to Motozintla S of Rancho Campeche, lat 15°18'34" N, long 92°22'27" W, Chiapas	5.08 ± 0.11
25	Whole rock, dacite, collected about 15 m from Chiapas-Guatemala boundary marker, Niquivil, lat 15°15'46" N, long 92°12'38" W, Chiapas	3.78 ± 0.16
26	Whole rock, andesite from summit of footpath from Berriozábel to Finca Hamburgo on the S side of Cerro Boquerón, Motozintla area, lat 15°15'10" N, long 92°16'34" W, Chiapas.	3.13 ± 0.07
27	Hornblende, unwelded tuff, 500 m S of Motozintla on highway to Buenos Aires, lat 15°20'46" N, long 92°15'40" W, Chiapas	1.62 ± 0.16

Table 3. Data for K-Ar ages in Tables 1 and 2

		Argon		
Sample No. (laboratory no.)	% K	Radiogenic $\times 10^{-12}$ moles/g	Atmospheric %	Age $\pm 1\,\sigma$ m.y.
1 (UAKA-74-25)	1.99	9.55 9.70	57.4 56.9	2.79 ± 0.08
2 (UAKA-74-23)	7.18	28.39 28.70	60.8 60.5	2.29 ± 0.07
3 (UAKA-74-22)	7.48	30.09 29.39	74.0 74.9	2.29 ± 0.10
4 (UAKA-74-24)	7.67	30.44 29.18	66.1 67.4	2.24 ± 0.08
5 (UAKA-74-21)	2.87	10.87 10.75	17.8 17.7	2.17 ± 0.04
6 (UAKA-74-32)	2.22	8.36 8.15	10.8 11.0	2.14 ± 0.04
7 (UAKA-74-31)	2.63	8.88 8.90	24.5 23.8	1.95 ± 0.04
8 (UAKA-74-33)	0.79_8	1.20 1.16	85.9 86.0	0.850 ± 0.030
9 (UAKA-74-30)	1.05	1.58 1.50	80.3 81.1	0.846 ± 0.024
10 (UAKA-74-34)	0.95_5	0.74 0.69	82.3 83.2	0.432 ± 0.029
11 Hbld. (UAKA-74-26)	1.20	0.24 0.26	96.3 96.0	0.120 ± 0.038
12 WR (UAKA-74-26)	2.28	0.85 0.80	87.1 87.9	0.209 ± 0.019
13 (UAKA-75-35)	7.28_4	281.4 281.6	16.0 16.6	22.2 ± 0.5
14 (UAKA-75-37)	7.73	251.0 251.8	27.9 27.7	18.7 ± 0.4
15 (UAKA-74-101)	0.024_2	0.73 0.77	92.9 92.4	17.8 ± 2.6
16 (UAKA-75-31)	7.58	193.8 199.2	35.7 33.4	14.9 ± 0.3
17 (UAKA-75-36)	7.63_4	178.0 179.0	12.8 12.4	13.4 ± 0.3
18 (UAKA-74-103)	7.42	169.3 167.4	17.4 18.3	13.0 ± 0.3
19 (UAKA-74-105)	7.11	151.3 154.0	51.4 51.1	12.4 ± 0.3
20 (UAKA-75-39)	7.41_2	134.4 138.5	38.5 37.6	10.6 ± 0.2
21 (UAKA-75-34)	7.62	123.5 125.3 126.2 128.1	54.0 41.8 54.2 43.4	9.95 ± 0.27
22 (UAKA-74-113)	7.72	83.2 82.7	26.4 26.4	6.18 ± 0.13
23 (UAKA-74-112)	7.28	72.2 73.2	30.1 29.7	5.75 ± 0.10
24 (UAKA-74-114)	6.96	61.7 61.2	37.9 39.5	5.08 ± 0.11
25 (UAKA-75-38)	2.50	16.13 16.69	73.8 73.3	3.78 ± 0.16
26 (UAKA-75-32)	1.92_4	10.44 10.45	22.9 21.5	3.13 ± 0.07
27 (UAKA-74-108)	0.45_6	1.36 1.21	86.8 88.2	1.62 ± 0.16

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