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PETROLOGY OF THE METAMORPHIC ROCKS OF ZACATECAS, ZAC., MEXICO

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RESUMEN

Metasedimentos triásicos, un intrusivo cretácico y rocas intrusivas terciarias comprenden los principales tipos litológicos al oeste de la ciudad de Zacatecas. Los metasedimentos son principalmente filitas que contienen lentes concordantes de cuarcita y mármol, y cuarcitas amoníferas de grano fino. El estudio detallado de la estratigrafía y estructura de las filitas sugiere que estas rocas fueron afectadas por dos episodios de deformación y metamorfismo durante el Jurásico Temprano y el Cretácico Tardío. Las dataciones por potasio argón en la moscovita de las filitas proporcionaron edades de 74.8 ± 1.5 y 73.2 ± 1.5 millones de años para el último episodio de metamorfismo. Los metasedimentos están intrusionados por una diorita plutónica somera. Las dataciones de potasio argón de la diorita sugieren una edad de la intrusión 73.8 ± 2.1 y 75.1 ± 1.9 millones de años. Los metasedimentos y la diorita están intrusionados por diques de riolita. La mineralización hipogénica dentro de los metasedimentos, la diorita, y la riolita intrusiva parecen haber ocurrido poco tiempo después de la intrusión de la riolita. La erosión subsecuente de los metasedimentos y de la diorita produjo la acumulación de un conglomerado cementado por calcita y hematita. El magmatismo continuó dentro del Terciario tardío con la extrusión de flujos de riolita, tobas y brechas volcánicas.

Todas las rocas metamórficas expuestas en el área de estudio pertenecen a la facies de esquistos verdes de metamorfísmo regional. Los rasgos químicos y petrográficos de las rocas metamórficas indican que un sistema relativamente seco pudo impedir que en las reacciones metamórficas entraran vestígios de minerales sedimentarios, resultando así asociaciones desequilibradas. La estrecha asociación en tiempo de los metasedimentos y la intrusión diorítica sugieren que las temperaturas necesarias para desarrollar la facies de metamorfismo de equistos verdes ocurrieron en profundidades someras en la corteza.

ABSTRACT

Triassic metasediments, a Cretaceous intrusive, and Tertiary intrusive rocks comprise the major rock types west of the city of Zacatecas. The metasediments are principally phyllites, containing conformable lenses of quartzite and marble, and fine-grained, ammonite-bearing quartzites. A detailed stratigraphic and structural study of the phyllites suggests that two episodes of deformation and accompanying metamorphism affected these rocks dur-

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ing Early Jurassic and Late Cretaceous time. K/Ar muscovite date for the phyllite yield ages of 74.8 ± 1.5 and 73.2 ± 1.5 m. y. for the last episode of metamorphism. The metasediments are intruded by a shallow diorite pluton. K/Ar whole-rock dates for the diorite set the age of intrusion at 73.8 ± 2.1 and 75.1 ± 1.9 m. y. Rhyolite dikes intrude the metasediments and the diorite. Hypogene mineralization within the metasediment, the diorite, and the intrusive rhyolite appear to have occurred not long after the intrusion of the rhyolite. Subsequent erosion of metasediment and diorite resulted in the accumulation of a calcite-and hematite-cemented conglomerate. Magmatism continued into the Late Tertiary with the extrusion of rhyolite flows, tuffs, and volcanic breccias.

All metamorphic rocks exposed in the area of study are of the greenschist facies of regional metamorphism. Chemical and petrographic features of the metamorphic rocks indicate that a relatively dry system may not have allowed relic sedimentary minerals to enter into metamorphic reactions, thus resulting in disequilibrium assemblages. The close association in time of the metasediments and the diorite intrusion suggests that the temperatures necessary for greenschist facies metamorphism were attained at shallow depths in the curst.

INTRODUCTION AND PREVIOS WORK

The Sierra de Zacatecas has been the site of mineral explotation since the mid-1500's, yet much remains to be learned about the geologic history of this region. This history is complicated by sparse exposure, folding and faulting of the metamorphic terrain, hydrothermal and deuteric alteration of the igneous rock, and at least one episode of ore mineralization. The objective of this study is to attempt to unravel the geologic history of the region in the light of new geological, petrological, and geochemical data.

The region of study, approximately 5 km wide and 7 km long, is located in the southern portion of the Zacatecas Quadrangle, located in the State of Zacatecas.

Occurring within this area are Mesozoic igneous and metamorphic rocks and Cenozoic igneous and sedimentary rocks. The metamorphic rocks are predominantly phyllites with lesser amounts of quartzite, metaconglomerate, and marble. Diorite and rhyolite constitute the igneous rocks. The only sedimentary rock exposed in the region is a red conglomerate composed chiefly of metamorphic and dioritic rock fragments. The Cenozoic igneous and sedimentary rocks, and the economic geology of the Zacatecas region have been the subject of two recent Master's theses at the University of New Orleans (Brown, 1976 and Barr, 1976). In light of this, this report will concentrate of the Mesozoic igneous and metamorphic rocks of the region.

Geologic mapping began with reconnaissance studies in January of 1973; but most of the mapping was accomplished during the months of June, July, and August, 1973.

Few geologic studies have been made of the Sierra de Zacatecas in spite of the great economic importance of the area. Prior to the late 1940's, published works consisted mainly of reconnaissance studies dealing with the entire State of Zacatecas, with only brief mention being made of the region in the vicinity of the city of Zacatecas (Burkart, 1836; Amador, 1900; Burckhardt, 1905; Flores 1906; Bastin, 1941). Burckhardt and Scalia (1906) were first to publish a modern geologic map of part of the Sierra de Zacatecas. A report by Mapes Vasquez (1949) relies heavily on this early work and is concerned principally with the ore mineralization. Edwards (1945) and a more recent report published by Pérez Martínez (1961) contain a geologic map and stratigraphic column nearly identical to those included in the report of Mapes Vasquez. Both publications are concerned more with the ore mineralization than with the structural and petrological nature of the rocks of the region.

REGIONAL SETTING

The area of study is part of the Mesa Central morphotectonic province of central Mexico. This province occupies the central portion of Mexico that lies south of the Monterrey-Torreon transverse segment of the Sierra Madre Oriental province and north of the Trans-Mexican Volcanic Belt (Figure 1). The eastern limit of the Mesa Central is marked by the largest morphotectonic province in Mexico, the Sierra Madre Oriental, which extends from the United States border to the Guatemala border.

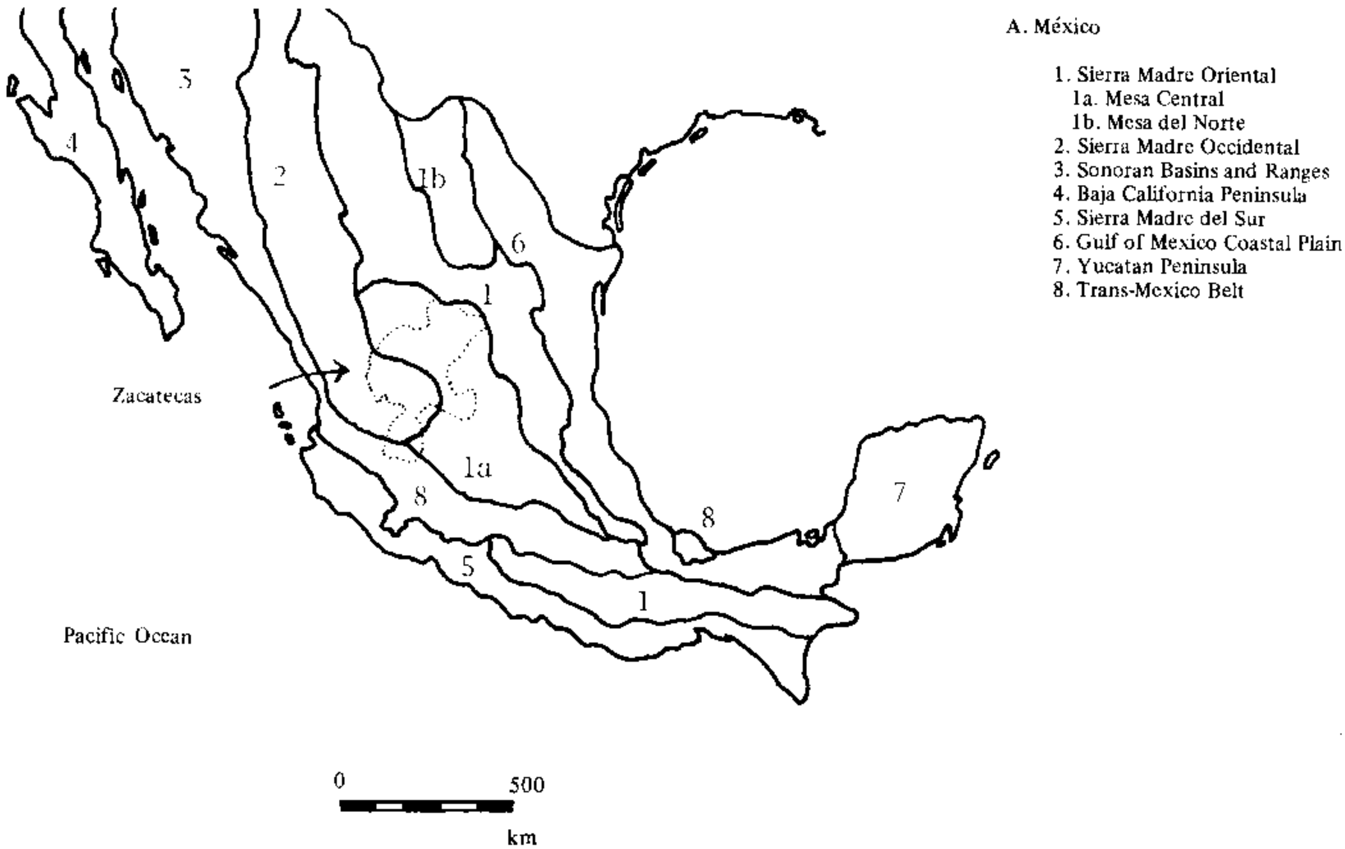

Figure 1. Morphotectonic units of Mexico (after Dengo, 1975).

Structurally, this province consists of parallel folded mountain ranges trending northwest-southeast, modified by thrusts and later normal faults (Guzmán and de Cserna, 1963).

The western edge of the Mesa Central is bounded by the Sierra Madre Occidental which extends from the United States-Mexico border southward to the Trans-Mexico Volcanic Belt. This province consists mainly of a basal sequence of andesitic to basaltic volcanic rocks overlain by dacitic and rhyolitic ignimbrites, tuffs, and lavas.

STRATIGRAPHY

Previous investigators of the Sierra de Zacatecas have described the rocks in the area in a general manner, and formational names, with one exception, have not been applied. Thus the formational names used in this report are being presented for the first time. The metamorphic rocks are refered to as the La Pimienta Phyllite of Triassic-Jurassic age. Other formational names used are the Las Pilas Diorite of Cretaceous age and the Zacatecas Conglomerate (Edwards, 1955), Cenozoic in age. Since the rhyolites are much more extensive south of this area and are the focus of another study (Brown, *op. cit.*), they are not formally subdivided in this report. Formational names have been taken from local place names.

La Pimienta Phyllite

La Pimienta Phyllite, which is best exposed in the deeper cut arroyos in the central portion of the área (particularly in the Arroyo La Pimienta, also known as Arroyo Talamantes), consists mainly of phyllite of variable appearance. Within the phyllite are conformable lenticular bodies of metaconglomerate, quartzite, and marble. Locally, the phyllite is tightly folded, with the fold axes trending to the northwest. This formation is the oldest unit in the field area. A detailed stratigraphic sequence present in the La Pimienta Phyllite is discussed below.

The stratigraphy of the La Pimienta Phyllite is complicated by folding and shearing, lithologic variation and paucity of outcrop. The topographic map, which served as a base for the general geologic map of the region, has a scale too small (1:16,700) to allow the recording of structural and stratigraphic information at intervals necessary for detailed geologic mapping. An enlarged map of the major arroyos shows the structural detail at a scale of 1:2,700 (Figure 2).

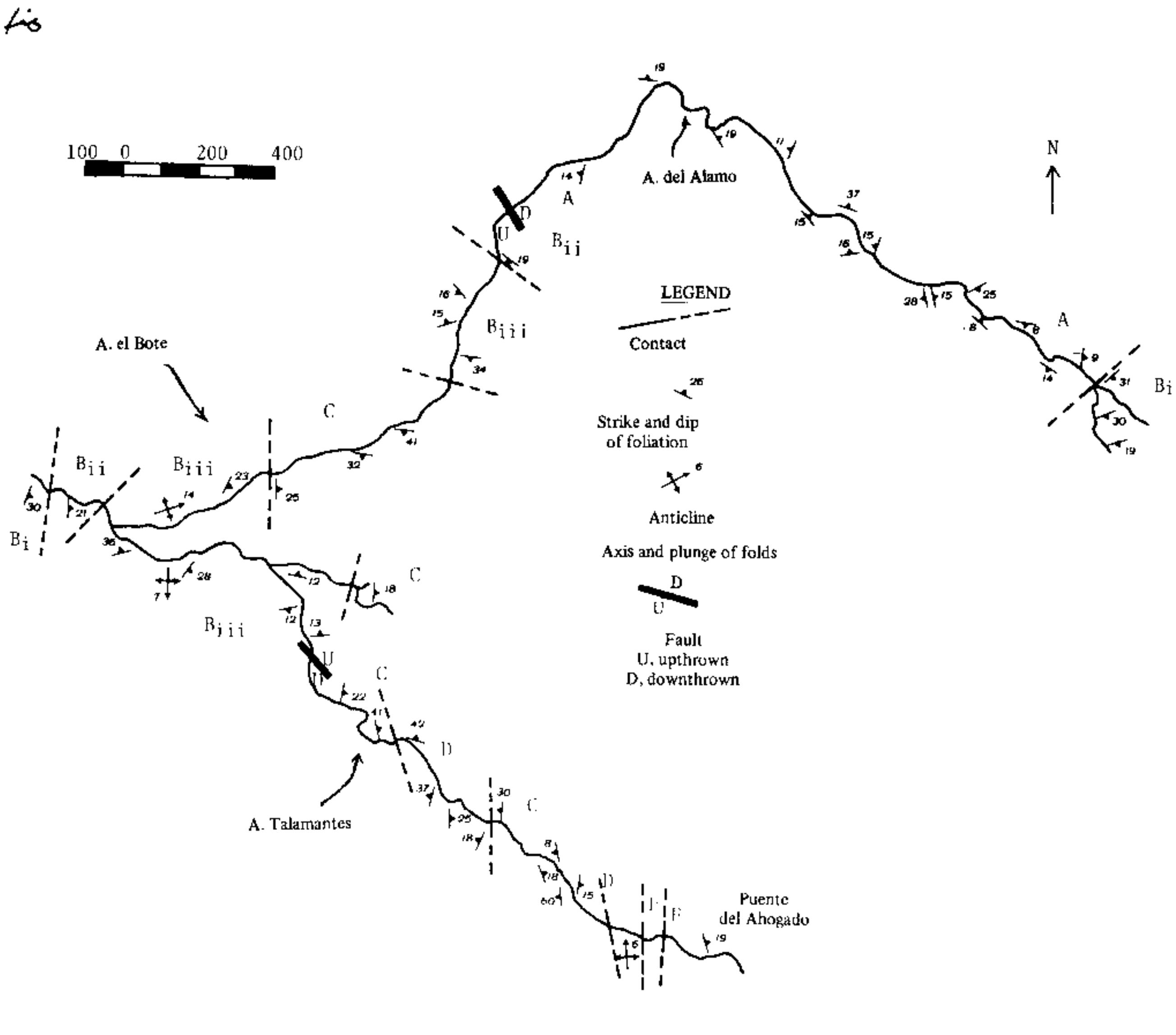

Figure 2. Geologic map along arroyos Talamantes, El Bote and Del Alamo (see text for description of units).

The results of a detailed study of Arroyos Talamantes, El Bote, and Del Alamo are shown in Figure 2 and Table 1. For reasons of simplicity and clarity, the stratigraphic units which were recognized in the La Pimienta Phyllite are designated by letters rather than names. Since there are almost no geopetal structures, the beds are assumed to be right side up and the age relations are based purely on stratigraphic position. Thicknesses were estimated with a five foot Jacob staff. Since contacts between some units are gradational and the structures complicated, thicknesses are only approximate. Color designations are taken from the Rock-Color Chart of Goddard *et al.* (1970).

Table 1. Summary of stratigraphic units defined in the La Pimienta Phyllite

UNIT G	Fine-grained, relatively homogeneous, dense. Metaquartzite. Thickness, uncertain.
UNIT F	Homogeneous, fine-grained, medium-dark-gray, slaty phyllite; contains metaquartzite lenses. Thickness, 55 m.
UNIT E	Coarse-grained, grayish-orange to moderate-yellowish-orange phyllite. Thickness, 8 m.
UNIT D	Intensely-folded, fine-grained, medium-bluish-gray phyllite. Thickness, uncertain.
UNIT C	Interbedded fine-grained, grayish-purple and grayish-orange phyllite; contains lenses of marble and metaconglomerate. Thickness, 50 m.
UNIT B	Member iii 45 m: Interbedded grayish-blue metaquartzite and grayish-brown phyllite. Member ii 25 m: Fine-grained, yellowish-gray phyllite. Member i 165: Fine-grained, grayish-orange phyllite.
UNIT A	Fine-grained, pale-purple to grayish-green schistose phyllite. Thickness, 30 m.

Unit A. The lowermost metamorphic unit, which is exposed in Arroyo del Alamo, is designated Unit A. It is a fine-grained (0.25 mm), pale purple (5 P 6/2) to grayish green (10 GY 5/2), schistose phyllite with a well-developed bedding-plane cleavage. Quartz and sericite compose approximately 50 and 40 percent of the rocks respectively, with minor talc, chlorite, and epidote accounting for the remaining 10 percent.

Despite the well-developed bedding-plane cleavage of the rocks in this unit, outcrops appear blocky when viewed from a distance of several meters. The strikes of bedding-plane cleavage range from northwesterly to northeasterly, but the angle of dip is consistently shallow. These shallow dips coupled with the fact that the Arroyo runs along strike account for the great extent of this unit. The estimated thickness of Unit A is 30 m.

Unit B. Above the lowermost unit in the section is Unit B, which is composed of three distinct members, designated i, i i, and i i i, with a total thickness of 325 m.

Member i, is approximately 165 m thick and is the most widespread member. It consists of grayish-orange (10 YR 7/4) to grayish-blue (5PB 5/2), very fine-grained phyllite which has a well-developed bedding-plane cleavage. The rock is characterized by uniform texture and mineralogy, and very fine grain size (0.06 mm). Quartz and sericite are present in about equal proportions and constitute 90 percent of the rock with accesory epidote (1 percent), alkali feldspar (5 to 7 percent), and opaque minerals (2 to 4 percent).

Member i i, with a thickness of only 25 mm, is the least extensive of the members in Unit B. This member is also a very-fine-grained (0.06 m), yelowish-gray (5Y 8/1) phyllite which has a well-developed bedding-plane cleavage. Quartz (50 percent) and sericite (40 percent) are the major minerals, with minor alkali feldspar (6 to 7 percent), epidote (1 percent), and chlorite (75 percent).

Member i i i, which is 45 m thick, is one of the most distinctive of all the metamorphic units and is best exposed at the ends of Arroyo Del Alamo and Arroyo Talamantes where they join to form Arroyo El Bote (Figure 2). Alternating thin layers of metaquartzite and phyllite make this member distinctive. The thickness of these layers ranges from 1 to 4 cm. Associated quartzite and phyllite layers usually have the same thickness. There is a definite grain-size gradation in one direction between the layers with the quartzite becoming finer grained and more micaceous toward the overlying phyllite layers; whereas the contact between the underlying phyllite and metaquartzite is sharp. Locally, relict graded bedding is useful in determing the tops of the beds.

The quartzite layers are grayish blue (5 PB 6/1) with small white specks of feldspar on fresh surfaces and light brownish gray (5 YR 6/1) to brownish gray ones (5 YR 4/1) on weathered surfaces. The quartzite lacks obvious foliation, but exhibits a crystalloblatic texture and is very hard. Quartz averaging 0.12 mm in size, constitutes 92 percent of the rock with minor amouts of sericite (8 percent). The amount of sericite increases and the grain size of the quartz decreases as the quartzite grades into the phyllite. In general, this quartzite is nearly identical to the lenticular bodies of quartzite which occur in overlying units.

The phyllitic layers of this member range in color from a moderate yellowish brown (10 YR 5/4) on a weathered surface to a grayish blue (5 PB 5/2) on fresh surfaces. Bedding-plane cleavage and phyllitic sheen are prominent features, and the grain size averages 0.06 mm. Quartz (45 percent) and sericite (45 percent) are the predominant minerals with accessory alkali feldspar (3 to 5 percent), epidote (1 percent), and lithic fragments (4 to 6 percent).

Small-scale folds characterize exposures of this member and structural measurements indicate a complex history of deformation. In general, the bedding-plane cleavage strikes to the northeast and dips at moderate angles to both the southeast and northwest.

Pods and lenses of metaconglomerate, which are characteristic of member i i i, occur both conformably and in fault contact with the interbedded phyllite and quartzite. The metaconglomerate lenses range in size from slightly less than 1 m to as much as 10 m across. The largest and best exposed outcrop of metaconglomerate appears to be in fault contact with the interbedded quartzite and phyllite. The color of the metaconglomerate is generally light brown (5 YR 5/6), and it contains particles ranging from 2 mm up to 10 cm. These multisized clasts are bound together by a fine-grained micaceous cement. Both small and large particles are flattened or elongated such that the long axes of all grains are subparallel.

Eighty to ninety percent of the clasts composing the metaconglomerate are quartzite, with the remaining ten to twenty percent being fragments of phyllite. Quartzite pebbles are rounded to well rounded, and phyllite fragments, which exhibit foliation, are rounded.

Unit C. Overlying Unit B are the multicolored phyllites that comprise Unit C. The associations and features that characterize this unit include the regular repetition of interbedded grayish-purple (5 PB 4/2) phyllite and grayish-orange (10 YR 7/4) phyllite, the prevalence of small-scale folding, small lenses of metaconglomerate, and burrow mottling in the grayish-purple phyllite. Conformable lenses of marble within the phyllite are an additional feature of this unit.

Both the grayish-purple and the grayish-orange phyllite possess bedding-plane cleavage and consists of very fine-grained (0.05 mm) quartz and sericite, which compose 50 and 45 percent of the rock respectively. Minor chlorite (3 percent) and epidote (2 percent) also are present. The grayish-purple phyllite typically contains remnant burrows. An extreme example of this burrow motling is a phyllite in which spots, averaging 3 mm in length, dot the rock.

Conglomerate lenses are confined mainly to the grayish-orange (10 YR 7/4) phyllite and are generally composed of at least 50 percent phyllite fragments. These fragments are arranged with their long axes subparallel and are associated with rounded grains of quartzite. Both types of clasts range in size from 2 mm to 30 mm, the average size being about 10 mm. Interstitial to these detrital clasts are secondary quartz and mixtures of fine-grained quartz and sericite, which bind the grains together. The abundance of phyllite fragments readily differentiates this metaconglomerate from that found in Unit B. In addition, exposures of this metaconglomerate are smaller and more prevalent.

Lenses of marble with exposures ranging in size from a few square meters to approximately 20 m^2 occur conformably within the phyllite of Unit C.

The weathered exterior of this marble is light brownish gray (5 YR 6/1) and the fresh surface is generally a light bluish gray (5 B 7/1). The marble is dominantly composed of very fine-grained (0.06 mm) calcite (80 percent) and minor amounts of quartz (8 percent) and sericite (12 percent). This very fine-grained calcite may coarsen to blocky, sparry calcite, and veins of secondary sparry calcite are abundant.

Locally the marble is intensely folded and foliated (Figure 3). This foliation is produced by the segregation of fine-grained, micaceous minerals into thin bands, which separate thicker layers of carbonate. At most exposures, however, the marble appears massive and unfolded. Bioclasts or even recrystallized bioclasts appear to be absent in the foliated and nonfoliated marble.

moderately steep dips to the east and to the west. The intense folding makes it difficult to determine the units' thickness. It is likely that this unit is intensely folded because of its relative incompetency. Most of the more competent units above and below are not as extensively deformed. In Arroyo Talamantes the Las Pilas Diorite intrudes this unit concordantly. Adjacent to the contact, lenses of diorite less than 1 m in length occur concordantly within the phyllite.

Unit E. The least extensive of the units in the section is Unit E. It consists of phyllite which is

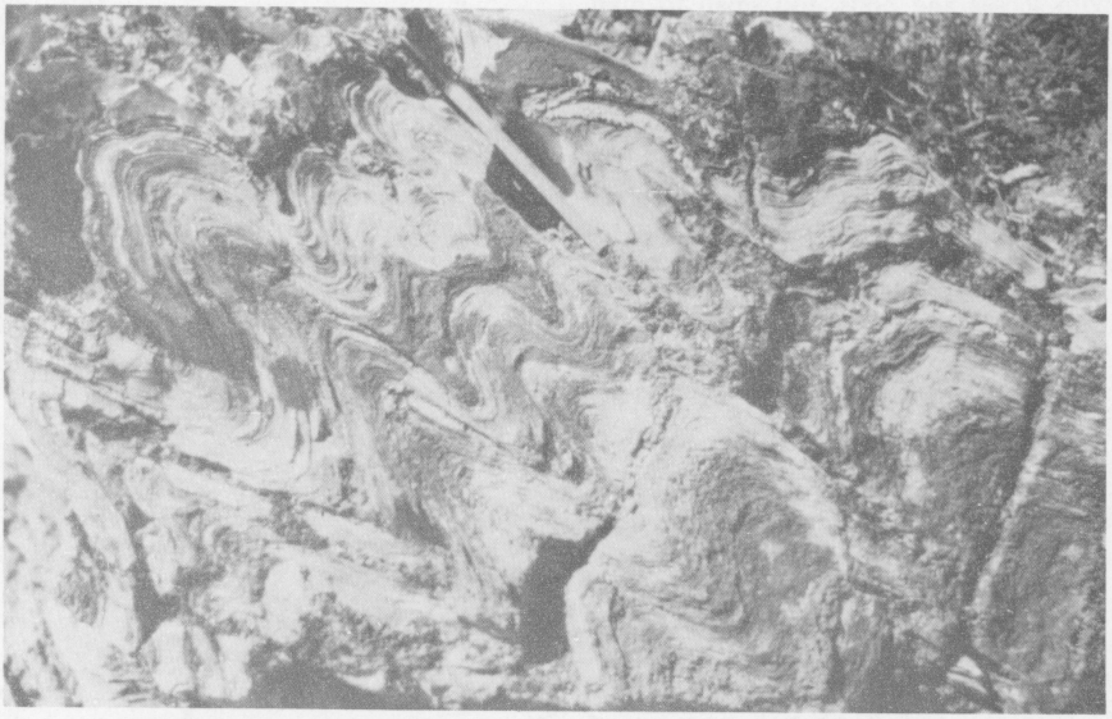

Figure 3. Isoclinal folding in a marble lens contained in *Unit C,* Arroyo Talamantes.

Unit D. This distinctive unit consists of medium-bluish-gray phyllite (5 B 5/1) with contorted layers and lenses of light colored minerals. Unit D is unique in its appearance and limited extent. The rock has bedding-plane cleavage and fine banding parallel to this cleavage. The dark portions of the rock are composed of very fine-grained quartz (0.06 mm) and opaque minerals. Aggregates of quartzofeldspathic minerals, as large as 1 cm in length, constitute the white portions of the rock. The contortion and weathering make accurate structural measurements difficult to obtain, but geneurally the foliation strikes north-south with

grayish orange (10 YR 6/2) on the weathered surface and moderate yellowish orange (10 YR 6/4) on fresh surfaces. Its coarser grain size (0.05 mm) is distinctive. Quartz (50 percent) and fine-grained muscovite (35 percent) predominate, but relict plagioclase and lithic fragments (10 to 12 percent), epidote (1 percent), and opaques (2 to 4 percent) occur in lesser amounts.

In as much as this unit is only 8 m thick, it does not provide much structural data. The few structural orientations obtained for bedding-plane cleavage are in accord with the general structural trend of the surrounding units.

Unit F. Is a homogeneous, medium-dark-gray (N4), slaty phyllite. The rock is so fine grained that individual mineral grains are not macroscopically visible. This extemely fine-grain size and a well-developed bedding-plane cleavage give the rock a slaty appearance. The cleavage consistently strikes approximately north-south and dips to the east at moderate angles. This unit lacks the small-scale folding that is characteristic of other units found further to the west in Arroyo Talamantes. The approximate thicknes of Unit F is 55 m.

Quartzite lenses and pods, too small to map, are present in all the metamorphic units, but Unit F contains a large lens of quartzite with a thickness approaching 10 m. The body has a tabular shape and because of its resistance to weathering can be traced for a short distance out of the Arroyo. The quartzite is hard and massive and is similar to the quartzite layers contained in member i i i of Unit B but it contains less clay than the quartzite of the interlayered member. The grain size is approximately 0.25 mm. Relict bedding can be distinguished in this quartzite and its orientation conforms with the bedding-plane cleavage in the surrounding phyllite.

Unit G. This unit consists of a very fine-grained (0.05 mm), dense quartzite composed of approximately 92 percent quartz and 8 percent sericite. Diorite dikes cutting through the quartzite are prevalent. Most exposures of Unit G occur as xenoliths, pendants (?) or intimately mixed diorite-quartzite. The true thickness of this unit is impossible to determine since it is the uppermost metasedimentary unit.

Structural Geology.

The structural orientations of the stratigraphic units described above are shown in Figure 2. Two-point maxima are obtained, suggesting two episodes of folding. Figure 5 is a plot ob both the poles to bedding-plane cleavage (contoured) and the trend and plunge of fold axes for rocks occurring only in Arroyo Talamantes. The two-point maxima obtained in this plot are more distinctly separated than the maxima in Figure 4, and the suggestion of two episodes of folding is stronger.

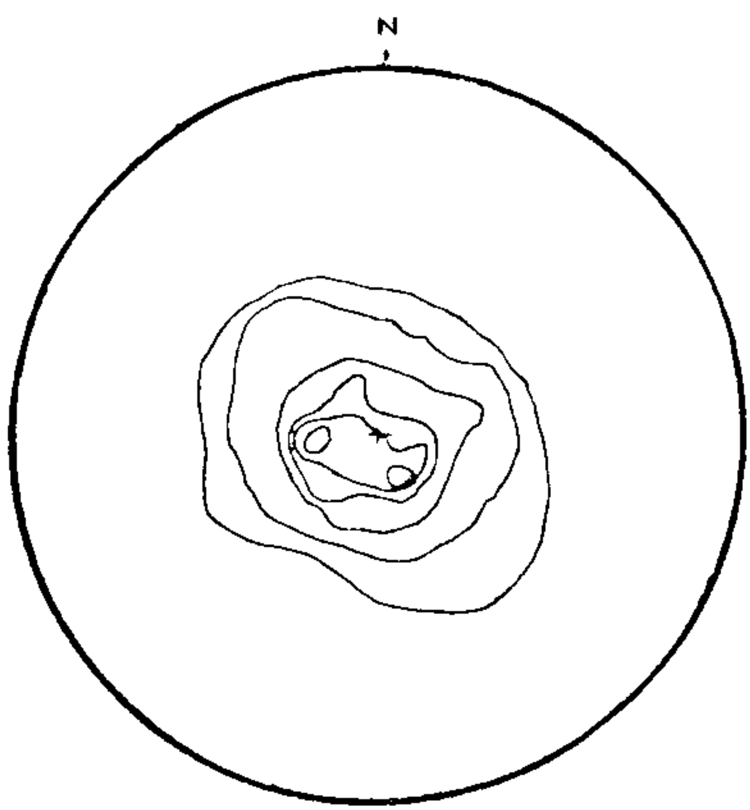

Figure 4. 119 poles to bedding – plane cleavage from arroyos Talamantes, El Bote and Del Alamo; contours 15 o/o, 13 o/o, 10o/o, 2 o/o, 1 o/o, 1 o/o, per 1 o/o area.

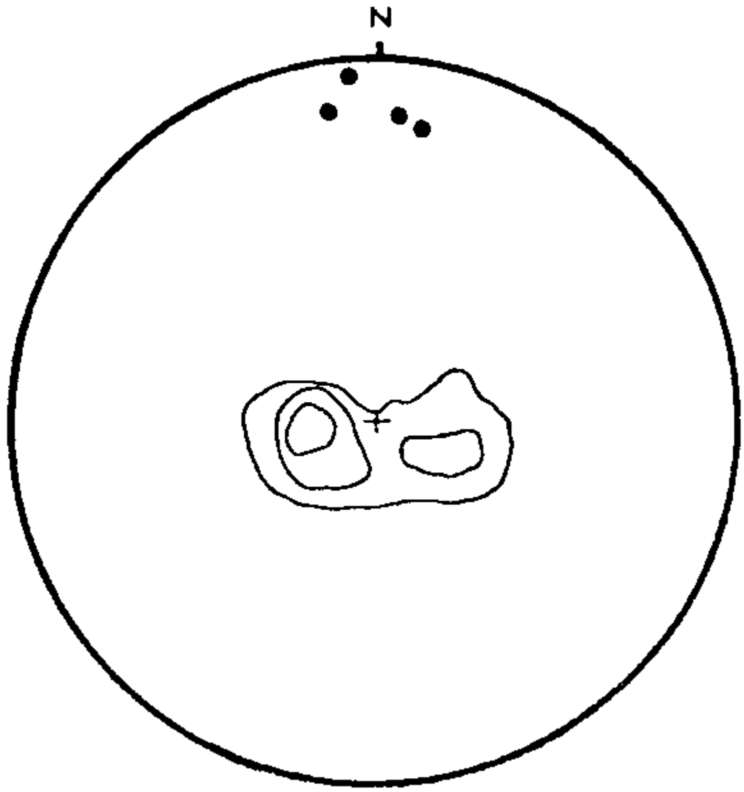

Figure 5. Trend and plunge of fold axes (o) and 42 poles to bedding – plane cleavage from Arroyo Talamantes; contours 10°/o, 5°/o, 2°/o per 1°/o area.

From these stereographic plot it cannot be concluded definitely that two episodes of deformation took place. Plotting of additional structural data may cause the two maxima described in Figures 4 and 5 above to merge into a single maximum. Two periods of folding are supported, however, by lenses of marble occurring conformably within the phyllites of Arroyo Talamantes, which show two directions of folding within a single hand specimen. Petrographic data, reported in a subsequent section of this paper also suggest two periods of folding for this region. Rocks of Units C and F contain a fracture cleavage consisting of microscopic fractures which disrupt and offset the primary cleavage.

These three lines of evidence (1) stereographic plots; (2) two directions of folding in carbonate lenses; and (3) petrofabric evidence, combine to produce a good, but not a conclusive case in favor of two episodes of deformation. The alternative of only a single deformation is less well suported by the present data and by the regional geologic history of Mexico, which documents at least two orogenic events after the deposition of the La Pimienta Phyllite, one probably during the very end of the early Jurassic and a second during the Late Cretaceous-early Tertiary (de Cserna, 1970).

Another important aspect of the structure of this area concerns the rather marked difference in structural complexity between Arroyo Talamantes and Arroyo del Alamo. Small-scale folding and contortion is prevalent in Arroyo Talamantes, whereas a uniform strike and rather shallow dip characterize the rock of Arroyo del Alamo. A possible explanation for the observed change in style of folding is difference in the competency of the stratigraphic units which predominate in the two arroyos. Most of the folding encountered in Arroyo Talamantes occurs in Units C and D. Unit D is highly contorted and is characterized by irregular aggregates and wavy bands of quartzo-feldspathic minerals, suggesting plastic flow. Unit C lacks mineral segregations and extreme contortion, but small-scale folds are more abundant than in any other unit, with the exception of Unit D. The deformation features of Units C and D indicate the incompetency of these units relative to the surrounding units, which are less intensely deformed.

No definite conclusiones can be drawn from the structural data gathered in the La Pimienta Phyllite. At present it appears that the rocks underwent two deformational events and that differences in structural complexity are probably due to differences in the competency of the rock.

Metamorphic Ages

Both Mapes Vazquez (*op. cit.*) and Pérez Martínez (*op. cit.*) agree with Burckhardt's (*op. cit.*) two different ages for metamorphic rocks in the Sierra de Zacatecas: "a schist and a schistose phyllite of Late Paleozoic age and a siliceous schist of Triassic age."

The schist and schistose phyllites are alleged to be separated from the overlying Triassic siliceous schist by a major unconformity. We have found no evidence of a major unconformity separating the metamorphic sequence. McGehee (1976) in his study of the La Pimienta metamorphics has also failed to find evidence of a major unconformity.

The late Paleozoic age assigned to the lowermost La Pimienta phyllite by Burckhardt (*op. cit.*) is based on fossil bivalves of the genus *Paleoneilo* Hall (1870), discussed in Pérez Martínez (*op. cit.*). Since the wide range of these bivalves makes them undersirable for correlation, the validity of this age is questionable from a paleontological standpoint. In addition, even after thoroughly searching, no fossil bivalves were found in the course of the present investigation. K/Ar muscovite dates of 74.8 ± 1.5 and 73.2 ± 1.5 million years, determined by Mobil Research and Development Corporation for samples of schistose phyllite, indicate only the age of the last episode of metamorphism.

The Triassic siliceous schist (Mapes Vazquez and Pérez Martínez) corresponds to the fine-grained, slaty phyllite in the upper part of the La Pimienta phyllite. The Triassic age for the siliceous schist is based on ammonite fragments which, according to Burckhardt (*op. cit.*) were derived from four species of ammonites. One of these species *Juvavites* (Anatomites) *mojsvari* Burckhardt, is known to be of Late Triassic age and has a definite occurrence in Mexico. No radiometric dates exist for the siliceous schist (fine-grained slaty phyllite of this report), but personal communication with J.A. Wolleben leads the authors to the conclusion that this age is reliable. As there is no evidence for an unconformity within the La Pimienta Phyllite, it is believed that the entire sequence is of late Triassic-Jurassic (?) age.

Las Pilas Diorite.

The Las Pilas Diorite, named after an arroyo ∿6 km north of Zacatecas, a greenish rock which ranges in grain size from aphanitic (0.1 mm) to medium-grained phaneritic (1-2 mm). Porphyritic diorite is present but rare. Widespread hydrothermal (deuteric?) alteration of the diorite has altered most of the primary mafic phases (pyroxene and rare olivine) to chlorite and fibrous amphiboles. Generally, the only recognizable phase in hand specimen is plagioclase. Exposures of the Las Pilas Diorite are weathered and typically display jointing and shearing. In as much as the diorite is almost always altered and weathered, classification of this (*op. cit.*), classified the "green rock" as diorite. Since *op. cit.*, classified the "green rock" as diorite. Since that time the names andesite, diabase, gabbro, and spilite have been applied. The name diorite is used herein chiefly because of the instrusive nature of the rock and its intermediate composition.

The Las Pilas Diorite has the characteristics of a hypabyssal intrusion. In places the diorite intrudes the La Pimienta Phyllite whereas in other areas, particularly to the north and east of the field area, it overlies the metasediments. The diorite-metasediment contacts range from concordant to discordant. Although the diorite is generally massive, locally a subtle foliation essentially parallel to the metamorphic foliation has been recognized. Diorites displaying this subtle foliation and concordant contacts, have previously been interpreted as "greenstone lavas which are penecontemporaneous with sediments" (Burckhardt and Scalia, *op. cit.;* de Cserna, *op. cit.,* 1970 and 1976). The diorite-phyllite relationships are here interpreted as a sytem of diorite feeder dikes cutting the strongly foliated phyllite and in places intruding along already existing foliation planes. The subtle foliation occassionally seen in the diorite is attributed to flow foliation upon intrusion. These feeder dikes are particularly well exposed along the new highway which borders the city of Zacatecas on the west and the north (for a detailed geologic section see Barr, *op. cit.*, pp. 13-14). Further evidence of a shallow intrusive origin for the diorite are its generally massive nature, its phaneritic grain size and the presence of isolated remnants of La Pimienta Phyllite found in and overlying the diorite (Barr, *op. cit.*). Additional data supporting a postsedimentary, intrusive origin for the diorite is presented in the section on Diorite Petrography.

The diorite which overlies the metasedimentary sequence (to the north and east of the field area) is interpreted as the contact between phyllite, and the base of the diorite intrusion, with the upper intrusive-phyllite contact having been removed by erosion. Pérez Martínez (*op. cit.*) has reached a similar conclusion and has classified the diorite pluton as a laccolith. We prefer the term hypabyssal intrusion since the absence of the upper diorite-metasediment contact prohibits a clear reconstruction of the overall geometry. McGehee (*op. cit.*) has suggested that this upper sequence of dioritic rocks may actually be a blanket of lava flows overlying the Phyllite. Although we favor an intrusive origin for the entire diorite sequence, an extrusive origin for part of the diorite cannot be excluded.

Zacatecas Conglomerate

The Zacatecas Conglomerate is composed chiefly of fragments of the La Pimienta Phyllite and the Las Pilas Diorite cemented by calcite and hematite. Subordinate amounts of quartz, and epidote are also present. The Zacatecas conglomerate is exposed only to the south of the Veta La Cantera where it unconformably overlies the Las Pilas Diorite. Pérez Martínez *op. cit.*, has assigned a tentative age of Late Oligocene or Early Miocene to the Zacatecas Conglomerate. For a more detailed description of the Zacatecas Conglomerate see Edwards *(op. cit.)*.

Rhyolite

Rhyolite flows blanket the tops of large mesas south of the city of Zacatecas and overlie the Las Pilas Diorite and the Zacatecas Conglomerate. Generally porphyritic, these rhyolite flows contain phenocrysts of quartz, sanidine, and biotite set in a mesostasis of glass or its devitrification products. Reconnaissance work to the south of Zacatecas shows that these flows are also present in this direction. Pérez Martínez (*op. cit.*) considers the flows to be Pliocene in age. Evidence for or against Pérez Martínez's selection of dates would require radiometric age determinations.

Silicified rhyolite also crops out northwest of and within the city of Zacatecas in the form of large enlongated dikes which cut the La Pimienta phyllite and the Las Pilas Diorite and typically cap the tops of peaks and ridges. This dense, silicified rhyolite is light in color, generally nonporphyritic and has vertical or near vertical flow banding. Quartz composes 90 o/o of the rock with minor amounts of opaque minerals and feldspars accounting for the remaining 10 o/o. These silicified rhyolite dikes are interpreted as feeder dikes for the more extensive rhyolite flows to the south. The most extensive exposures of the oldest rock types, the La Pimienta Phyllite occur west of the city of Zacatecas indicating that erosion has exposed the deepest levels in this vicinity. Thus it is likely that in this area the overlying rhyolite flows have been eroded and only the silicified rhyolite feeder dikes remain as evidence of the rhyolite volcanism. The silicification of these rhyolite dikes occurred in conjunction with the mineralization of the Las Pilas Diorite and the La Pimienta Metasediments (Barr, *op. cit.*).

PETROGRAPHY

The description and classification of the rock types encountered in the course of geologic mapping are presented along with specific examples of texture and mineralogy of individual rock samples. Tables 2a and 2b summarize the mineralogy for each rock type. All phases were studied by conventional optical techniques. Selected plagioclase feldspars were studied by X-ray diffraction and the 4-axis universal stage. Whole-rock X-ray diffraction studies were made for most samples.

Metamorphic Rocks

The most abundant metamorphic rocks in the field area are phyllites, some of which have slaty or schistose affinites. The predominant minerals are quartz and sericite, but minor amounts of alkali feldspar, plagioclase feldspar, epidote, chlorite, biotite, and iron oxides are present. Many of these minerals are sedimentary relics, and the rocks display relict sedimentary textures and characteristics. All phyllites are the product of greenschist facies regional metamorphism, and they are primarily metasandstones and metasiltstones. Relict lithic fragments and relict sedimentary minerals, such as

TABLE 2a. Petrographic Summary of Igneous Rock Types

		Diorita	Intrusive tyolite	Rhyolite flows	Rhyolite tuffs
Qtz	Phenocrysts		+	+	+
Kf		±	±	+	+
Pf		+		+	+
Mus					
Bio				+	+
Amp				±	±
Cpx		+			
01		±			
Qtz	Groundmass		+	+	+
Kf		+	±	+	+
Pf		+		+	±
Mus		+		±	±
Bio		±		±	±
Chl		+			
Amp		+			
Cpx		+			
Epi		+			
Mgt		+	±	±	
Hem		+	+	+	+
Phy		±	±		

TABLE 2b. Petrographic Summary of Metamorphic Rocky Types

		Phyllite/Schist	Metaquartzite	Marble
Qtz	Porphyroblasts	+	+	+
Kf		+	±	
Pf		±	±	
Mus		+		
Bio				
Chl				
Cht				
Cal				+
Qtz	Groundmass	+	+	+
Kf		+		
Pf		± +		
Mus		+	+	±
Bio		±		
Chl		± ±		±
Cht		±		
Cal		±		+
Epi		+	±	±
Hem		+		±
Lim		+	±	

Qtz = quartz, Kf = K feldspar, Pf = plagioclase feldspar, Mus = muscovite, Bio = biotite, Amp = amphibole, Cpx = clinopyrosene, 01 = olivine, Chl = chlorite, Cht = chloritoid, Cal = calcite, Epi = opidote, Mgt = magnetite, Hem = hematite, Lim = limonite, Phy = pyrite.

plagioclase and alkali feldspar, are present in variable proportions. These mineral relics indicate that the premetamorphic lithologies included subarkoses and sublitharenites. Relict sedimentary textures include rounded to wellrounded grains and almost totally matrix supported grains surrouded fine-grained, micaceous material. These relict sedimentary textures are characteristic and their presence can be attributed to the low grade of metamorphism which only partially recrystallized the sediments.

For phyllites which have undergone a slightly higher degree of metamorphism, the sixe of relics decreases and crystal boundaries become sutured, developing a crystalloblastic texture. In the case of quartz, porphyroblasts begin to form. Additional metamorphic textures of these higher grade rocks include cataclastic texture and the development of foliation. Phyllites occurring in fault or shear zones, display both megascopic and microscopic cataclastic textures. In hand specimen angular quartz grains are set in a fine-grained (0.1 mm), powdery matix. This rock has a talc-like feel, and the foliation is disrupted by abundant small fractures. Microscopically, the matrix is highly disrupted and consists of very finegrained (0.01 mm) sericite, talc, and quartz. Microfolding and microshering of the matrix is prevalent. Large quartz grains (0.6 mm) are angular and fractured. Almost all the phyllites examined in thin section possess one direction of foliation, as evidenced by the parallel alignment of micaceous minerals. A second cleavage, consisting of small fractures, disrupt and offset the original cleavage. The fracture cleavage is usually associated with microcrenulations.

Conformable marble and quartzite lenses occur within the phyllite. The marble and the quartzite are essentially monomineralic, but sericite (5 to 10 percent) is also present in both and locally is abundant in the marble. Marbles containing thin layers of sericite display foliation, whereas the quartzite is always massive. Mosaic texture is prevalent in the marble, whereas that of the quarzite is crystalloblastic with incipient mosaic texture. Relict sedimentary textures generally are not present in either the marble or the quartzite. The premetamorphic lithologies were limestones and quartzarenites, both of which contained aluminous clays.

The mineralogy of the metamorphic rocks is dominated by quartz and sericite. Quartz is abundant throughout the phyllites, attaining its greatest concentration in the quartzites (92 percent) and greatly diminishing in percentage in the marbles (5 to 7 percent). Large quartz grains (0.3–0.4 mm) display relict sedimentary rounding. In rocks showing more advanced recrystallization, quartz grains are smaller and exhibit sutured boundaries and Boehm lamellae. Clear quartz porphyroblasts, having incipient augen structure, are locally present.

Fine-grained quartz (35 to 45 percent) with sutured borders composes the groundmass of most of the phyllites.

Groundmass quartz is usually interspersed with sericite, and grains show slight elongation, with long axes subparallel to the long axes of sericite flakes.

Relict quartz grains show a variety of extinction types, ranging from undulose to straight, and contain minute inclusions. Quartz that shows evidence of recrystallization is typically free of inclusions and has straight extinction.

Relict alkali feldspars and plagioclase feldspars are generally present in all phyllites in amounts not exceeding 5 percent each. These relict grains are large (0.2 mm) and have rounded boundaries that are altered to sericite. Plagioclase exhibits combined albite and carlsbad twinning and is generally fresher in appearance than alkali feldspar. An contents are quite variable, ranging from An_{38} to a low of An_8.

Feldspars produced by metamorphic recrystallization include albite and rarely microcline. Both are present in the groundmass and as small porphyroblasts. Porphyroblasts are unaltered, free of inclusions, and have straight extinction. Metamorphic albite is present in most of the phyllites, whereas metamorphic microcline is a rare constituent.

Sericite (45 to 60 percent) is the dominant phase in the phyllites and is generally present in small amounts (5 to 10 percent) in the quartzites and marbles. It occurs in the groundmass as very fine (0.02 mm) parallel plates or aggregates of plates that may or may not be closely associated with very fine-grained quartz. Biotite and chlorite are minor phases which are absent in some sections. Both minerals are fine grained and occur with sericite.

Epidote (1 percent) and clinozoisite (1 percent) are accessory minerals in all phyllites, increasing in abundance in rock[6] in which reclystallization in the coarser portions of the rock appears to be more complete. These minerals are widely dispersed in the groundmass but show a slight tendency towards association with quartz. Both minerals have a prismatic habit and, because of their very small size (average 0.015 mm), are distinguished only with difficulty.

Calcite is present in the phyllites and quartzites only as secondary vein and cavity fillings. In the marbles calcite is the dominant phase and occurs both as large grains of sparry calcite and as fine-grained calcite.

Hematite and limonite are present in the phyllite and are distinguished by their optical properties in reflected and transmitted light. Hematite (1 to 2 percent) is less abundant than limonite and occurs as elongated, feathery masses, lying parallel to planes of foliation.

Lithic fragments occur in phyllites which have been incompletely recrystallized. Most fragments are fine grained and of uncertain mineralogy. Lithic fragments are large (0.5-0.8 mm), equalling the size of the largest grains in the rock, and their shapes range from angular to rounded. Sericitization typically obscures fragment borders and makes primary mineralogy unrecognizable.

In order to better illustrate the textural and mineralogical characteristics of the metamorphic rocks, the detailed petrology of a representative phyllite and marble is presented below.

Sample 8 is representative of the phyllites that have been subjected to metamorphism of an intensity high enough to have destroyed most relict sedimentary textures and minerals. In hand specimen it is fine grained, foliated, and micaceous. In thin section the major phases, quartz and sericite, are accompanied by alkali feldspar, plagioclase, iron oxides and hydroxides, and minor biotite. Quartz forms microporphyroblasts (0.2–0.3 mm) which have wavy extinction and typically show incipient augen structure. Microporphyroblasts of albite have a similar size and shape. Relict sedimentary plagioclase feldspars (An_{8-10}) displaying albite twinning are abundant as are irregularly shaped masses of iron oxides and hydroxides. These phases are contained in a matrix of very fine-grained (0.04 mm) quartz and sericite with minor amounts of biotite. Micaceous constitutents of the matrix are aligned but locally are disrupted by the growth of quartz and albite microporphyroblasts.

In hand specimen, sample 26 is a homogeneous finegrained marble. Microscopic examination reveals the presence of quartz and pyrite in addition to calcite. Small grains of quartz (0.04–0.06 mm) are widely dispersed in the section. Generally, they are angular, contain minute inclusions, and have straight extinction. Calcite ranges in grain size from less than 0.005 mm to 0.3 mm. Large anhedral grains exhibit rhombohedral cleavage and occur with other large grains as patches in the matrix or in crosscutting veins. Fine-grained calcite forms a mosaic texture that composes the matrix in which the larger grains reside. Pyrite occurs as scattered euhedral cubes.

Diorite

The texture of the diorite is probably best illustrated by describing the textures of representative diorite samples. Generally, diorite is altered to the extent that primary texture and mineralogy are obscured. Sample 25 is a diorite that, in spite of some alteration, still retains its original textural and mineralogical features. In hand specimen light-gray feldspar phenocrysts are set in a greenish-colored, fine-grained matrix which is cut by thin white veinlets of calcite. In thin section abundant plagioclase laths (0.5–1 mm) and subordinate pyroxene phenocrysts (0.5–0.8 mm) are in an intergranular groundmass of pyroxene, glagioclase, sericite, and chlorite (Figure 6).

Sample 52 is light gray in hand specimen and consists primarily of large (1–3 mm) plagioclase phenocrysts. Examination of the thin section reveals that some parts of the slide exhibit intergranular texture, with chlorite, fibrous amphiboles, and rarely pyroxene filling the interstices between plagioclase laths (Figure 7). Elsewhere in the slide

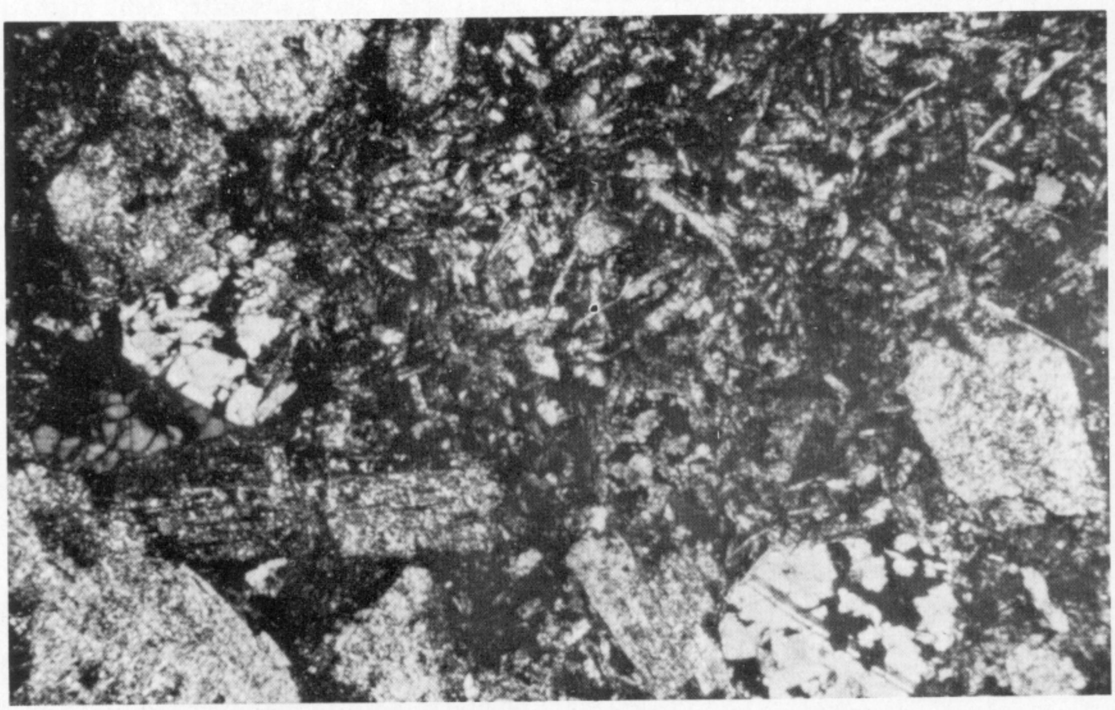

Figure 6. Photomicrograph of a relatively fresh diorite (sample No. 25) containing augitic clinopyroxene and sericitized plagioclase set in a matrix of dominantly plagioclase and chlorite (crossed-nicols).

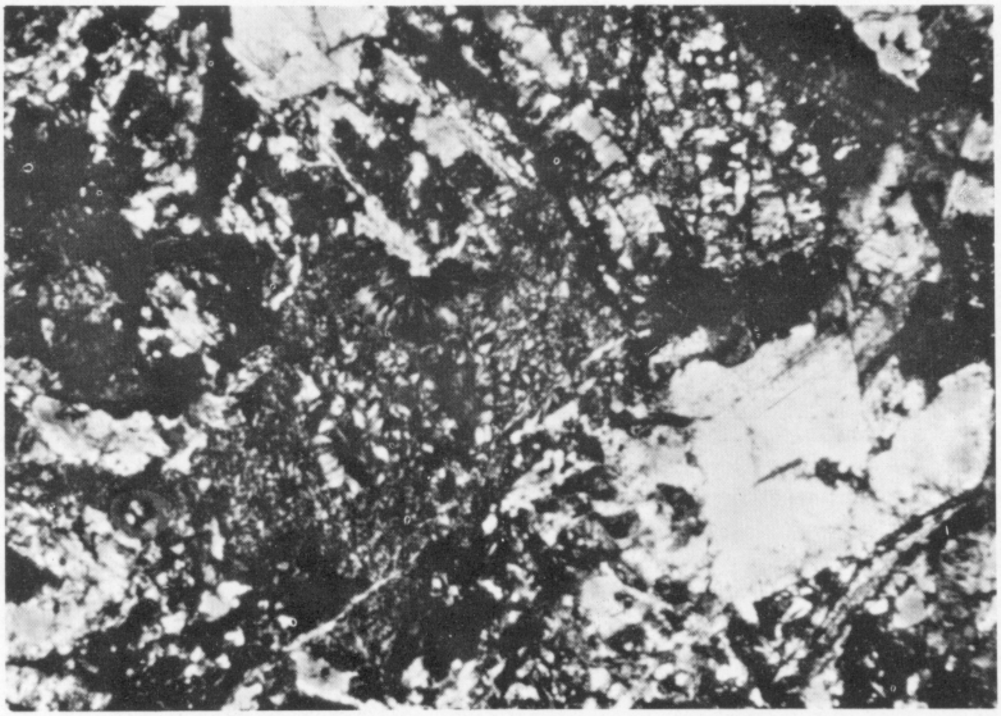

Figure 7. Photomicrograph of a hydrothermally (deuterically) altered diorite (sample No. 52) containing plagioclase and chlorite (crossed-nicols).

hypidiomorphic granular texture is dominant and plagioclase laths interlock with few interstices.

Plagioclase feldspars are the most abundant mineral in the diorite, accounting for 50 to 70 percent of the rock. Plagioclase laths occurring both in the groundmass and as microphennocrysts are subhedral to euhedral. Groundmass plagioclase, accompanied by mafic minerals, fills the interstices between microphenocrysts of pyroxene and plagioclase.

The Rittman Zone method and the four-axis universal-stage method of Slemmons (1962) were used to make determinations of plagioclase An contents. The An contents range from An_{38} to An_{12} and average approximately An_{24}. These values refer to microphenocrysts alone because the groundmass plagioclase is, too fine grained and generally too altered to allow compositional determinations. The alteration products are sericite and minor epidote. Twinning of the plagioclase is generally according to the ablite or carlsbad twin laws, and microphenocrysts most typically exhibit continuous normal zoning.

Porphyritic diorite sample 53 was crushed and the plagioclase phenocrysts were removed. Some of the phenocrysts were separated for later x-ray diffraction study. Other phenocrysts were wrapped in platinum foil and heated in a graphite crucible with an oxygen-acetylene torch, producing a plagioclase glass. The refractive index of this glass was determined to be 1.506 in sodium light. Using the Schairer (1956) curve, which plots index of refraction of plagioclase glass against anorthite content, a composition of An_{24} was obtained.

Additional plagioclase was separated by heavy liquid from twelve other powdered diorite samples whose An content had been previously determined on the universal stage in order to determine their structural states. X-ray diffraction patterns were run for all the plagioclase. For plagioclase with An contents between An_{20} and An_{40}, Smith (1956) suggests that the separation of 131 and 131 be used to determine the structural state of plagioclase.

The resulting $20_{131} - 20_{131}$ values are plotted against An content on the graph of Bambauer *et* *al.*, (1967) and the results of this study are given in Figure 8.

All the samples plot near the plagioclase low curve, indicating that the plagioclase is ordered, probably as a result of slow cooling. The structural state of the plagioclase and the field relations, taken together, strongly suggest an intrusive origin for the diorite (Ranson *et al.*, 1975).

Alkali feldspar is present in most of the diorites, but in amounts less than 10 percent. It occurs in the groundmass with plagioclase and as stubby, subhedral to anhedral microphenocrysts. Recognition of the alkali feldspar is difficult because of its close association with plagioclase, and its alteration to sericite.

Olivine is rare in the diorites, and its positive identification was made only in a few thin sections. In these thin sections the olivine occurred as corroded and altered microphenocrysts associated with pyroxene. Alteration products are primarily chlorite and fibrous amphiboles.

Phyroxene is the most abundant primary mafic phase and generally accounts for 15 to 25 percent of the fiorite. It typically occurs as subhedral microphenocrysts in a matrix of fine-grained plagioclase, pyroxene, and chlorite. Rarely anhedral pyroxene crystals fill the interestices between plagioclase microphenocrysts. The diorite appears to contain only augitic clinopyroxene. Orthopyroxene was not identified.

The diorite mineralogy, particularly the absence

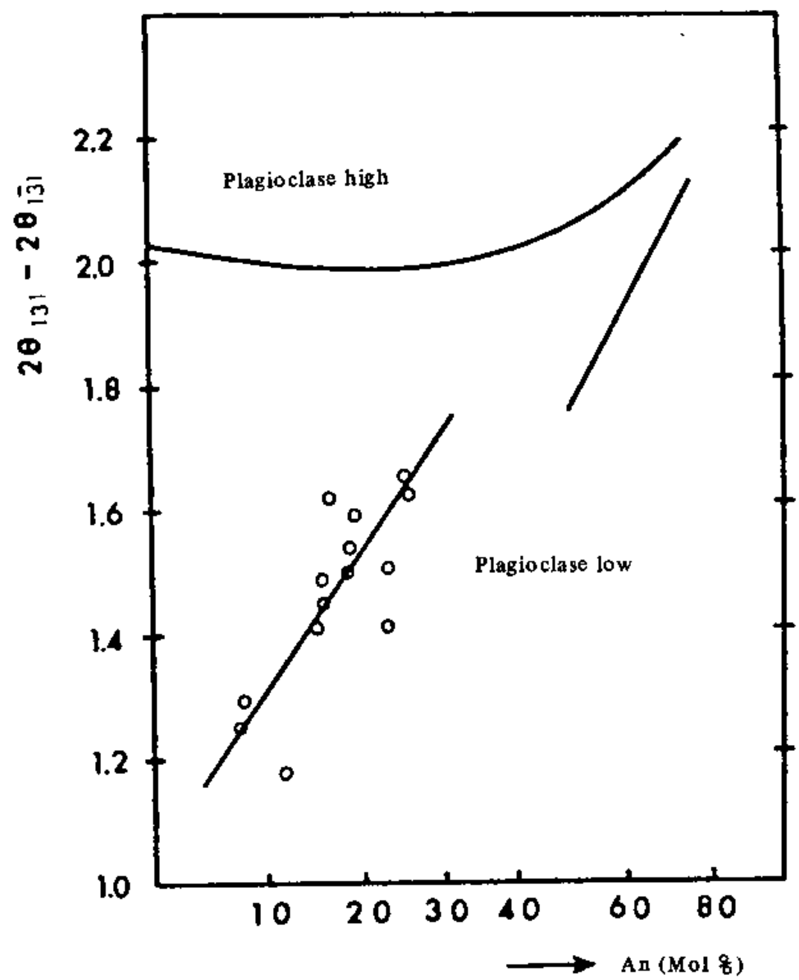

Figure 8. Boundary curves for the variation of $\Delta\theta = 2\theta_{131} - 2\theta_{131}$ (Cukα, radiation) and An content for plagioclase (o) from Zacatecas Diorite.

of albite, a ubiquitous mineral in greenschist facies "greenstones", and the intersertal texture of chlorite in lieu of well oriented grains typical of metamorphic chlorites, although not conclusive, supports our thesis that the diorite has not been metamorphosed but instead has been extensively altered deuterically and/or hydrothermally.

PETROCHEMISTRY AND PETROGENESIS

Analyses of 16 samples of igneous and metamorphic rock (Tables 3 and 4) were performed by X-ray spectrography and atomic absorption spectromety. Si, Al, Ti, Fe, Ca, K, Mn, Rb, and Sr were analyzed by X-ray fluorescence and Na and Mg were determined by atomic absorption techniques. The concentration of water was determined for selected samples by a modification of the Penfield method (Shapiro and Brannock, 1956).

Metamorphic Rocks

There is noticeable variation in the major chemistry of the metamorphic rock samples. Chemical variation in metamorphic rocks may be caused by differences in original composition and differences brought about by the later migration of elements. In as much as these rocks are of low metamorphic grade, the observed variation is considered to be principally the result of differences in original composition. Most of the original variation can be attributed to original differences in the amounts of quartz, feldspar, and clay in the premetamorphic rocks.

Table 3. Chemical Analysis of Metamorphic Rock Types

Sample No.	8	9	10	11	13	14	15	17	18	31
Major and minor constituents (o/o)										
SiO_2	65.5	75.1	82.1	78.1	75.5	85.6	84.6	64.9	77.9	68.1
Al_2O_3	21.0	10.3	12.1	11.1	9.9	9.9	9.3	17.6	12.0	14.1
Fe_2O_3 1	6.05	4.14	2.60	2.88	4.79	2.98	2.52	4.31	2.77	3.72
MgO	0.48	1.32	0.41	0.51	0.45	0.24	0.03	0.25	0.59	0.42
CaO	0.13	0.15	0.07	0.22	0.21	0.05	1.33	0.35	0.17	0.51
Na_2O	0.94	1.21	0.50	2.54	0.85	0.85	1.33	0.55	0.90	0.14
K_2O	5.70	3.80	3.35	1.81	1.81	1.70	1.83	4.12	5.49	7.60
TiO_2	0.62	0.53	0.32	0.34	0.62	0.45	0.57	0.97	0.19	0.80
MnO	0.07	0.07	0.04	0.04	0.07	0.07	0.05	0.06	0.02	1.21
H_2O		1.60						4.10	0.02	
Sum	100.49	98.22	101.49	97.54	94.20	101.84	101.56	97.21	100.05	97.00
Trace Elements (ppm)										
Rb	224	169	100	62	68	139	93	189	191	171
Sr	98	105	45	108	143	88	74	75	100	75
Rb/Sr	2.29	1.61	2.22	0.57	0.47	1.58	1.25	2.52	1.91	2.28

Total iron calculated as Fe_2O_3

Table 4. Chemical Analyses of Las Pilas Diorite

Sample No.	24	25	32	35	54	AA*
Major and minor constituents (o/o)						
SiO_2	65.6	49.3	59.5	57.9	52.1	54.20
Al_2O_3	12.8	11.9	11.0	17.2	15.3	17.17
$Fe_2O_3^{**}$	4.60	9.18	11.10	5.69	10.26	8.97
MgO	0.52	3.08	1.81	1.42	2.12	4.36
CaO	2.67	9.47	1.90	10.70	7.44	7.92
Na_2O	1.62	2.99	2.03	0.23	4.24	3.67
K_2O	4.77	5.24	4.67	0.25	0.19	1.11
TiO_2	0.54	1.04	0.18	0.65	1.32	1.31
MnO	0.12	0.17	0.25	0.09	0.17	0.15
H_2O	3.20	3.90	3.40	4.00	3.90	0.86
Sum	96.45	96.27	95.84	98.13	97.04	100.00
Trace Elements (ppm)						
Rb	131	66	81	32	17	
Sr	241	456	176	133	301	
Rb/Sr	0.54	0.14	0.46	0.24	0.06	

* Average composition of andesite (Nockolds, 1954); total also includes 0.28 percent P_2O_5
** Total iron calculated as Fe_2O_3

Chemical data from Table 3 are plotted on ACF and A'KF diagrams (total iron calculated as FeO) for the greenschist facies of both Barrovian and Abukuma-type regional metamorphism (Figure 9a, 9b, and 10). Chemical data plotted on an AFM diagram is shown in Figure 11. The metamorphic and relict mineral assemblages for each rock are given in Table 5. Stable mineral assemblages in Figure 9a include: pyrophyllite + epidote + chloritoid; chloritoid + epidote + chlorite; muscovite + chloritoid + chlorite; and muscovite + microcline + chlorite. Quartz and albite also may be present in the above assamblages. In Figure 9a stable mineral assemblages, with the addition of quartz and albite, are: pyrophyllite + epidote + chloritoid, and muscovite + chlorite + biotite. For Abukuma-type metamorphism (Figure 10) the stable assemblages with the addition of quartz and albite, are. pyrophyllite + epidote + chlorite; muscovite + pyrophyllite + chlorite; muscovite + chlorite + biotite, and muscovite + biotite + microcline. Microscopic examination and X-ray diffraction studies have failed to positively identify chloritoid and pyrophyllite, even though Figures 9, 10 and 11 indicate that the samples studied have the correct bulk chemistry needed for the formation of these minerals. Sericite is ubiquitous in all samples plotted on the ternary diagrams, and pyrophyllite may actually be present but not recognized due to the difficulty in distinguishing pyrophyllite from sericite optically. Also if pyrophyllite composes less than ten percent of the rock, it would be difficult

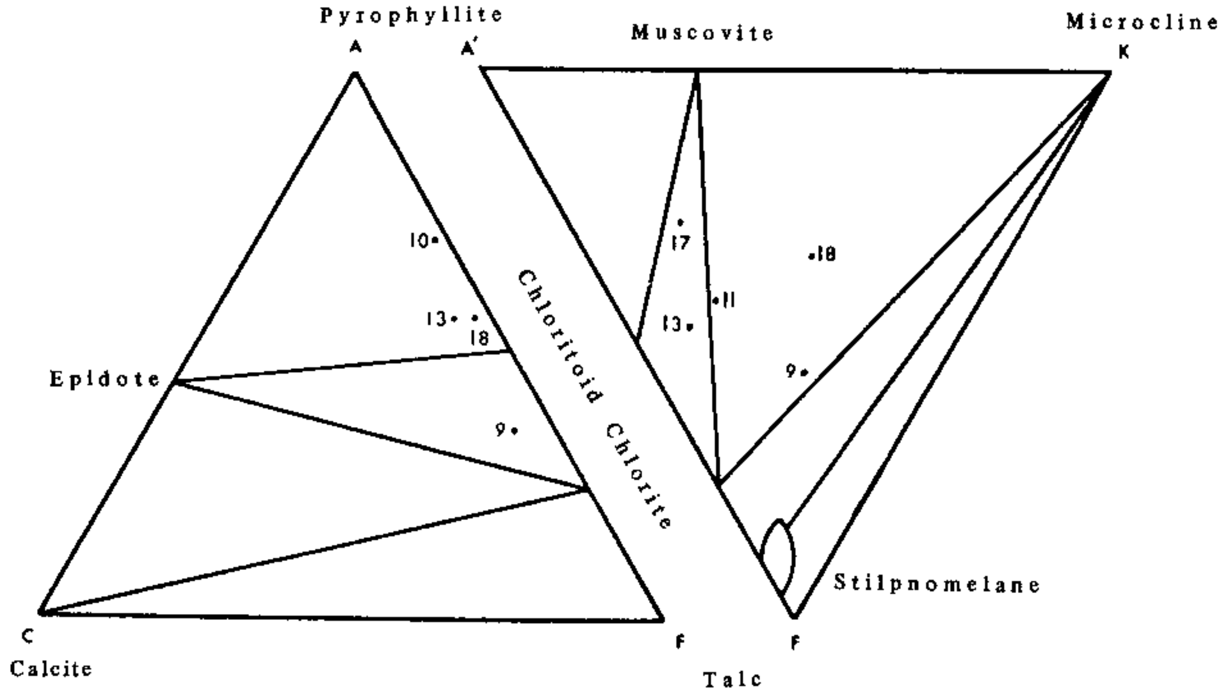

Figure 9. Rock samples from Table 6 plotted on ACF and A'KF diagrams for the quartz – albite – muscovite-chlorite subfacies of the greenschist facies of Barrovian-type regional metamorphism.

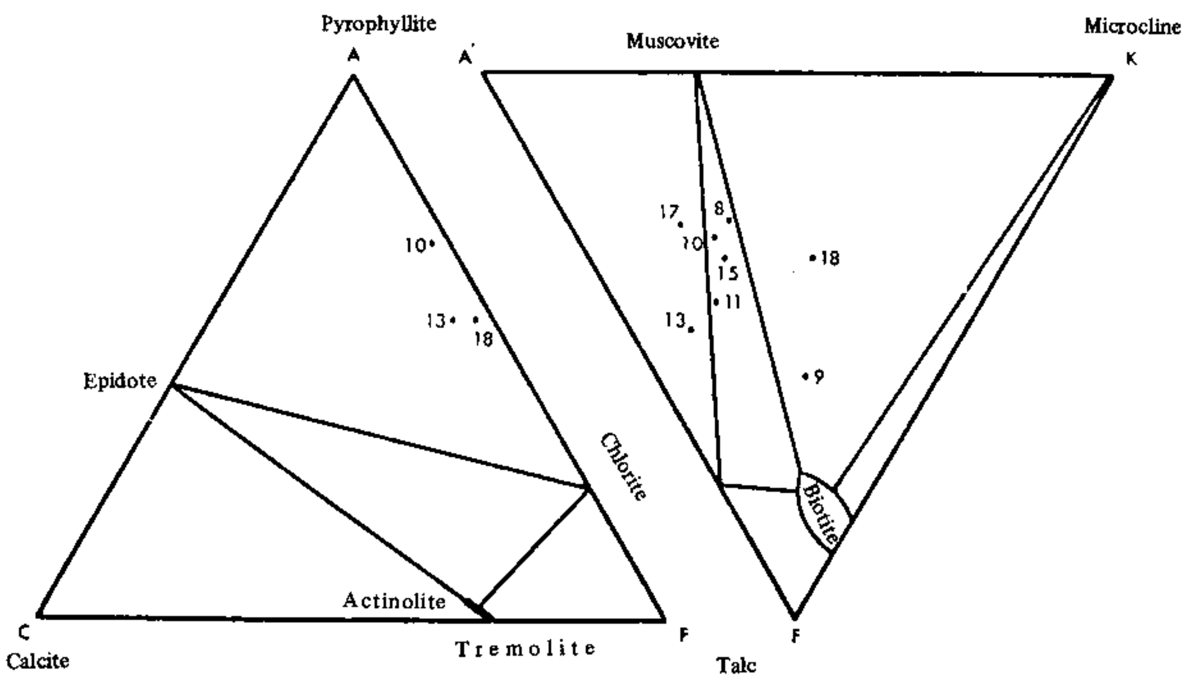

Figure 10. Rock samples from Table 6 plotted on ACF and A'KF diagrams for the quartz – albite – muscovite – biotite – chlorite subfacies of the greenschist facies of Abukuma-type regional metamorphism.

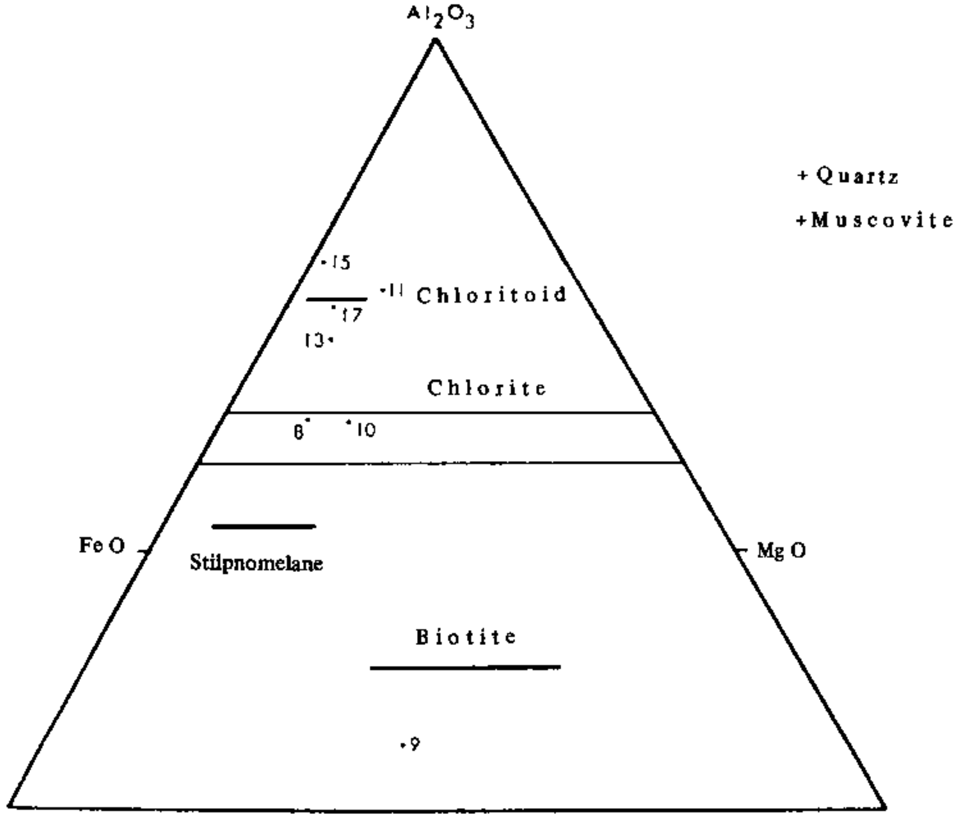

Figure 11. Rock samples from Table 6 plotted on the AFM projection plane.

to detect by whole-rock X-ray diffraction. For similar reasons minor amounts of chloritoid, which closely resembles some of the chlorites, may have escaped detection. An alternative explanation for the absence of chloritoid may be that a disequilibrium assemblage is present. Relict minerals and textures suggests that some minerals did not react completely during metamorphism.

Previously cited age data demonstrate that concomitant with metamorphism was the intrusion of the diorite, which probably resulted in the dehydration of the intruded metasediments. Slower reaction rates, resulting from a dehydrated system, may have prevented the reaction of certain minerals which could have led to the observed disequilibrium assemblage. Further study, centered around the chemistry of individual mineral phases, is necessary before the detail of these reactions can be successfully learned.

In conclusion, the metamorphic mineral assemblages (Table 5) are indicative of greenschist facies regional metamorphism. Disequilibrium assemblages may be present in some rocks as a result of the dehydration of the system by a shallow intrusive of diorite composition. The close association in time of the metamorphism and the intrusion suggests that the temperatures necessary for greenschist facies metamorphism were attained at shallow depths in the crust. Thus, metamorphism in this region can probably be characterized best as Abukuma-type metamorphism.

Las Pilas Diorite

The Las Pilas Diorite has undergone extreme alteration. Five analyzed samples of diorite (Table 4) show that major and minor element concentrations vary considerably amoung themselves and with respect to the average composition of andesite (Nockolds, 1954). K_2O is anomalously abundant in three samples, but falls to less than 0.3 percent in the remaining two rocks. Na_2O is equally inconsistent, ranging from 4.24 percent to 0.23

Table 5. Summary of Metamorphic and Relict Mineral Assemblages of Analyzed Metamorphic Rocks

Sample No.	Observed Metamorphic Assemblage	Relict Assemblage
8	quartz + albite + muscovite ± chlorite ± biotite	plagioclase + alkali feldspar
9	quartz + albite + muscovite + epidote ± chlorite	plagioclase ± alkali feldspar
10	quartz ± albite + muscovite ± biotite ± chlorite + epidote	——
11	quartz + muscovite ± chloritoid	quartz + alkali feldspar
13	quartz + albite + muscovite ± epidote ± chlorite	quartz + alkali feldspar
15	quartz + muscovite ± biotite	quartz + plagioclase + alkali feldspar
17	quartz + muscovite + chlorite	——
18	quartz + albite + muscovite + epidote ± chlorite ± talc	quartz + alkali feldspar

percent. The trace elements Rb and Sr are present in concentrations to be expected for rocks of dioritic composition and yield Rb/Sr ration of less than 0.6. K/Rb ratios ranging from 78 up to 794 again reflect the widely differing chemical composition of diorite. The relatively high water content, is as would be expected based on the abundance of the chlorite and actionolite.

The anomalous chemistry and altered mineralogy apear to be the result of both hydrothermal and deuteric alteration. Along diorite-metasediment contacts the alternation is most likely hydrothermal and is probably associated with a later episode of hypogene mineralization. Elsewhere in the diorite deuteric alteration is thought to have produced the mineralogical and chemical changes. The pervasiveness of the deuteric alteration may better be described as autometamorphism. Age and structural relationships indicate that the intrusion of the Las Pilas Diorite was concurrent with the deformation an metamorphism of the La Pimienta Phyllite. Intrusion of a relatively dry diorite magma into a sequence of sediments undergoing greenschist facies metamorphism would probably result in the production of hot aqueous solution in amounts sufficient to have produced the pervasive autometamorphism of diorite.

GEOLOGIC HISTORY

The pre-Mesozoic geologic history of Mexico, particularly that of the Precambrian and Early Paleozoic, is poorly known. Outcrops of Precambrian and Paleozoic rocks are known in the Sierra Madre Oriental province (Guzman and de Cserna, *op. cit.* 1961 and the Cserna, *op. cit.* 1970), but an understanding of the history of these rocks is limited by their geographic separation and limited exposure. The oldest known rocks are schist and gneiss of Precambrian age, which crop out in eastern Hidalgo and in west-central Tamaulipas (Guzmán and de Cserna, *op. cit.*). In northern Oaxaca a granite-schist-pegmatite complex way also be of Precambrian age. Kesler and Heath (1970) indicate that the latter Precambrian complex extends into the states of Puebla and Guerrero.

Paleozoic sedimentary rocks are known to exist in four main areas; the Sonora, Chihuahua, Tlaxico and Chiapas Guatemala basins (Dengo, 1975). With the exception of the Sonora basin the others align along a common axis. Dengo (*op. cit.*) suggests that initially the locus for Paleozoic sedimentation was a series of aligned basins, each with its own sedimentary history, which later developed into a single geosyncline. López Ramos (1969), on the other hand, suggests that during the Paleozoic a geosynclinal through extended from western Coahuila to Tamaulipas, through Querétaro, San Luis Potosí and Zacatecas.

The Paleozoic tectonic history is particularly difficult to unravel since the data is scanty and has been amassed from locations separated by considerable distances. The early Paleozoic metasedimentary rocks in Mexico are believed to belong to two separate tectonic belts bordering a central granitic and metamorphic cratonic backbone (Guzman and de Cserna, *op. cit.;* Dengo, *op. cit.*). These two belts, the Jaliscoan on the west and the Huastecan on the east, were sites of Paleozoic geosynclinal sedimentation. Both the Huastecan and the Jaliscoan structural belts were metamorphosed and underwent anatexis during middle Paleozoic time. According to Dengo (*op. cit.*) downwarping along the axis of the cratonic backbone initiated as local basins that finally emerged into a single geosyncline that formed the locus of sedimentation for the Paleozoic sedimentary rocks. Dengo therefore, proposes that this tectonic element be considered a separate tectonic belt.

De Cserna (*op. cit.,* 1970 and 1976) postulates an Early Jurassic deformation in central Mexico that produced the Zacatecas–Guanajuato thrust fault which super imposed eugeosynclinal deposits on Upper Triassic continental redbeds. Evidence for this thrusting, cited by de Cserna, comes from the area under investigation in this report. De Cserna (*op. cit.,* 1970) describes the Upper Triassic rocks just west of the city of Zacatecas, on the basis of sections presented by Burckhardt and Scalia (*op. cit.*) as consisting of "about 200 m of marine shales, silt– and sandstones and interbedded spilitic andesites and related volcanics which the general term of 'greenstones" very aptly describes." He believes that these rocks are in contact with Paleozoic or Precambrian schists, and that the "greenstones" are indicative of an eugeosynclinal environment, with miogeosynclinal rocks lacking. Additionally, he feels that the schist-Upper Triassic contact might very well be a folded thrust. These conclusions are unsupported by our observations. First, in addition to the sediments mentioned by de Cserna (*op. cit.,* 1970), metaconglomerate, quartzite, and marble are widespread, and these are more representative of miogeosynclinal than eugeosynclinal deposits. Second, the Zacatecas "greenstones" do not appear to be volcanics but, instead, intrusive diorite related to a shallow pluton that intruded the Triassic metasediments. Finally, there is no substantial evidence that the Upper Triassic rocks referred to by de Cserna (*op. cit.,* 1970) rest unconformably on Paleozoic or Precambrian schists (phyllite and schistose phyllite of this report). In addition, we have found no evidence that supports the contention that the metamorphics referred to by de Cserna are of Precambrian or Paleozoic age; they appear instead to be Mesozoic.

De Cserna (*op. cit.,* 1970) considers the Early Jurassic orogeny, which included thrusting along the Zacatecas–Guanajuato thrust front, to be an established event in northern and south-central Mexico. This orogeny, which is probably equivalent to a phase of the Nevadan orogeny, appears to correspond well with the first period of deformation and metamorphism determined by our study of the rocks near Zacatecas.

During the Middle Jurassic-Early Cretaceous interval, tectonic activity was limited to the subsidence of northern Mexico, and inundation of northeastern Mexico was completed by the end of the Early Cretaceous. More intense tectonic activity was revewed in northern and south-central Mexico in the Late Cretaceous and Early Tertiary and this activity produced folding, metamorhpism, intrusion and a marked change in the sedimentation pattern of northern Mexico (De cserna, *op. cit.,* 1970). These events mark the beginning of the Laramide or Hidalgoan orogeny and are synchronous with the events that occurred near Zacatecas as indicated by the K/Ar muscovite dates of 74.8 ± 1.5 and 73.2 ± 1.5 million years for the phyllite. These dates which indicate the last episode of metamorphism closely correspond with the dates for the diorite (73.8 ± 2.1 and 75.1 ± 1.9 million years) and indicate that the intrusion and the metamorphism were penecontemporaneous. Since there is no contact metamorphism associated with the diorite sill, it is reasonably certain that the ages for the phyllite represent the actual time of metamorphism, rather than the time of argon loss due to the heat produced by the intrusive. The possible second phase of folding and metamorphism detected in the rocks at Zacatecas is probably the result of some later period of Laramide activity.

The duration of the Laramide orogeny in Mexico is not yet known, but with the start of the Eocene, volcanism became more widespread in northeast and south-central Mexico. At Zacatecas rhyolite dikes intruded the La Pimienta Phyllite and the Las Pilas Diorite. Faulting and erosion taking place at this time led to the deposition of the Zacatecas Conglomerate. After an interval of time of uncertain length, hypogene mineralization occurred, chiefly as hydrothermal veins which cut through the La Pimienta Phyllite, the Las Pilas Diorite, and the silicified rhyolite. The absence of mineralized veins in the rhyolite flows, at least in those presently exposed, suggests that these volcanic rocks were emplaced after the ore mineralization. These ignimbrite sheets, which thicken substantially to the south, appear to have erupted at approximately the same time, Miocene-Oligocene (Claubaugh and McDowell, 1976), as the extensive ignimbrite sheets of the Sierra Madre Occidental (Brown, *op. cit.*).

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