CARBONIFEROUS ISLAND-ARC AND ASSOCIATED ROCKS
FROM THE MISION CALAMAJUE AREA, BAJA
CALIFORNIA, MEXICO

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geological Sciences

by
John H. Hoobs
Spring 1985
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Approved by:

[Signatures]

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CHAPTER 1

INTRODUCTION AND REGIONAL GEOLOGY

INTRODUCTION

Purpose of Study

Metamorphosed pre-batholithic volcanic and sedimentary rocks in the Mision Calamajué area of Baja California Norte include strata of Carboniferous age. The purpose of this study is to describe the lithology and stratigraphy of the pre-batholithic terrane and to determine its age. The Carboniferous volcanic and sedimentary rocks have been subjected to lower green-schist metamorphism and shear cleavage parallel to bedding. Age correlations based on conodonts and comparisons with lithologically similar strata in western North America suggest that these rocks may have been deposited in a southern extension of the Carboniferous inner-arc basin between the Antler Orogenic highland and the Klamath-Northern Sierra Nevada island-arc. A chapter on tectonic implications discusses the present geographic position of these Carboniferous rocks in relation to other lithologically similar units in the Cordillera.
Location and Accessibility

The study area is located near the Jesuit mission of Calamajué, deserted in 1767 (Baegert, 1771), approximately 35 km south of the fishing village of Puerto Calamajué on the coast of the Gulf of California (Figure 1).

A dirt road, leading from Rancho Chapala, located on Mexican Highway 1, east to Puerto Calamajué, passes through the northwestern part of the study area and may be traveled by a conventional vehicle. Another dirt road leads south from this road, through the southeastern part of the study area, Arroyo Calamajué, and intersects Mexican Highway 1, 25 km to the south. This ungraded road is accessible only by a four-wheel drive vehicle due to the unpredictability of road conditions resulting from flash flooding.

Physical Geography

The study area falls within the Gulf of California geomorphic subprovince of Baja California, an area characterized by desert basins and ranges lying between the main gulf escarpment to the west and the gulf shore to the east. Pre-batholithic rocks are exposed in Sierra Calamajué between the main gulf escarpment, just to the west of the study area, and the Gonzaga lineament
Figure 1. Map showing location of study area east of Rancho Chapala, near Mision Calamajué, Baja California Norte, Mexico.
to the east along the western foot of Sierra la Asamblea. This would put the study area at the extreme southern end of the Gonzaga block, originally defined by Gastil and others (1975).

Four main drainages in the study area are Las Palmas, Piedra de Afilar, Tinaja de los Frailes and Calamajué which all eventually drain north toward Bahía Calamajué on the Gulf of California. Elevations range from 300 m in the northern part of Arroyo Calamajué to 1,040 m on top of C. Colorado.

**Previous Work**

The first published work specifically mentioning the Mision Calamajué area was by a botanist in 1792, who made a reconnaissance expedition of Baja California to record the plants, animals, minerals, hot springs and other natural phenomena (Longinos Martinez, 1792). He wrote the following account of Mision Calamajué:

> In this canyon there are veins of silver and gold which have never been worked, doubtless because of the desert nature of the place and the want of every facility. Throughout the district there are hills which can be seen from a distance to be green with an abundance of Copperas [p. 29].

The abandoned mines located in the study area are a single gold mine (El Toro) and a marble mine (Marmol) near the abandoned mission and unmarked abandoned
copper mines in the northwestern part of the study area (Plate I).

The green hills seen in the distance by Longinos Martinez are actually foliated, bright green basic volcanics (Plates I & II).

The most comprehensive piece of work, to date, dealing with the regional aspects of Baja California is that of Gastil and others (1975), which provided basic mapping and stratigraphy of the region. Their report and that of Gastil and Miller (1983), briefly mention volcanic rocks in the Mision Calamajué area as being part of the Cretaceous Alisitos Formation. Associated sedimentary rocks were considered by Gastil and Miller (1983) as possibly Mesozoic on the basis of their lithologic association with the "Middle" Cretaceous rocks of La Olvidada (Phillips, 1984).

The first mention of Carboniferous rocks in Mision Calamajué is by Gastil and Miller (1984) which was based upon work done by this author and the identification of conodonts. Briefly mentioned is the occurrence of Carboniferous conodonts in bioclastic limestones at the top of a metasedimentary section overlain by volcanic strata of unknown age.
Method of Study

Field work for this study included 45 days between December 1983 and October 1984, excluding the summer months because of extreme heat. Field work consisted of geologic mapping on a topographic base prepared by the Departamento de Estudios del Territorio Nacional. The scale of the base was 1:50,000 at a contour interval of 20 m. For field purposes the scale was increased to 1:16,667 with the final map presented at this scale (Plate I). Aerial photographs at a scale of 1:25,000 were valuable for regional structural analysis.

Fifty-two standard petrographic thin-sections were studied and described to determine mineral composition and microstructures (Appendix A).

Carbonate samples were dissolved in 10 percent acetic acid for the extraction of microfossils.

About 50 mg of zircon was separated from about 150 Kg of volcanic rock by conventional heavy-mineral separation techniques. One zircon subfaction was analyzed for its U/Pb isotopes and plotted on a concordia diagram (Appendix C).

Terminology

For most of the rocks described in this study, original sedimentary and volcanic textures predominate
over metamorphic textures, and sedimentary and volcanic terminology is sometimes used in conjunction with the prefix "meta". Classification of terrigenous rocks follows Folk (1974) if metamorphism has not obliterated original textures and compositions. Protoliths for argillaceous phyllites are from Picard (1971). Dunhum's (1962) classification for carbonates was used on the limestones and classification of volcanic rocks follows phenocryst assemblages from Streckeisen (1979). For rocks in which metamorphism obscures the volcanic and sedimentary textures, description of metamorphic textures follows the usage of Spry (1969).

REGIONAL GEOLOGY

Peninsular California lies east of the Continental Borderland and west of the San Andreas fault system, and is part of the Pacific Plate. Rocks of Peninsular California were intruded by the Peninsular Ranges Batholith during mid to late Mesozoic time. Emplacement of these batholithic rocks climaxed during "medial" Cretaceous time. This history allows for convenient division of the stratigraphic record into pre-"middle" Cretaceous (pre-batholithic) rocks and post-"middle" Cretaceous (post-batholithic) rocks first proposed by
Gastil and others (1975).

The following descriptions apply to pre-batholithic, batholithic, and post-batholithic rocks as they appear in the study area (Plate I, back pocket).

Pre-Batholithic Rocks

The metamorphosed pre-batholithic volcanic and sedimentary rocks are exposed in "profile view" in Arroyo Calamajué canyon with the base of the mapped section to the south and the top of the section to the northeast. These rocks are Carboniferous in age. Lower greenschist regional metamorphism characterizes the pre-batholithic strata. The pre-batholithic sedimentary and volcanic rocks have been divided into six units and two subunits for purposes of stratigraphic discussion (Plate II).

Batholithic Rocks

Granitic rocks within and surrounding the study area are part of the Peninsular Ranges Batholith. Plutons of granodiorite composition are found intruding the Carboniferous rocks in the southwestern and northwestern part of the study area (Plate I, symbol Kgr). Smaller plutons and dikes of gabbro are present in the north and northwest part of the study area (Plate I,
symbol Ki). Field relations indicate that the gabbro was emplaced before the granodiorite.

**Post-Batholithic Rocks**

Sedimentary rocks. An angular unconformity separates the folded Carboniferous strata from the tilted Tertiary sedimentary rocks. Post-batholithic sedimentary rocks are preserved in the southern part of the study area (Plate I, symbol Ts). These semi-consolidated sediments consist of cross-bedded, pinkish-gray weathered, arkosic sands, with minor conglomerate and tuff beds. Invertebrate and vertebrate fossils have been collected from similar rocks in Punta Prieta, 40 km south of the study area (Morris, 1966 and 1968). An Early Eocene (Wasatchian) Vertebrate assemblage is preserved at Punta Prieta in these non-marine sedimentary rocks (Flynn, et al., 1984).

Travertine deposits are present in large quantities in most canyons and occur as flat-lying, white or dirty brown deposits draped over the Carboniferous pre-batholithic rocks. They were not mapped in this project as their extent is usually restricted to the canyons in the study area and have a close association with the Quaternary alluvial deposits (Plate I, symbol Qa1).
Volcanic rocks. Flat-lying volcanic rocks cap an isolated peak in the northern part of the study area (Plate I, symbol Tv) and are composed of hornblende basalt. Gastil and others (1975) mapped similar volcanic rocks in adjacent areas as Miocene andesites and undifferentiated Miocene volcanics.
CHAPTER 2

CARBONIFEROUS STRATIGRAPHY

INTRODUCTION

The metamorphosed sedimentary and volcanic rocks of the Mision Calamajué area are divided into six informal field units, two subunits and one marker bed. The measured section for the stratigraphic column is exposed within Arroyo Calamajué canyon in the southeastern part of the 120 square km study area. The total measured section is 6,100 m in apparent thickness. Plate II (back pocket) is a diagrammatic columnar section of the Mision Calamajué units, and includes summarized descriptions of each unit.

This chapter includes a lithologic description of each unit followed by discussions on protolith, depositional environment and, where possible, a provenance interpretation from petrographic studies (Appendix A).

UNIT A

Description

The metamorphosed sedimentary rocks of unit A, exposed at the base of the measured stratigraphic
section is a nonresistant unit having an apparent thickness of 1,000 m. The base of the unit is marked by intrusion of granodiorite of the Peninsular Ranges Batholith shown as Kgr on Plate I. The unit is exposed in only a small part of the southeastern portion of the study area, and is covered by Quaternary alluvium to the east, and intruded by granodiorite to the west.

The overall nature of unit A is a coarsening upward sequence characterized by the predominance of a thin-bedded quartz-mica phyllite containing bedded chert intervals low in the section. Bedded chert intervals decreases in thickness upsection, and the ratio of phyllite to chert increases. The unit is capped by 20 to 30 m of chert litharenite containing intervals of pebbly conglomerate and limestone. Limestone occurs within the upper 50 m and is interbedded with both the phyllite and chert litharenite. The chert and limestone intervals occur as massive beds surrounded by the less competent and less resistant phyllite, and can only rarely be traced laterally for large distances. Commonly these more resistant intervals appear lenticular in shape due to boudinage structures and appear only weakly foliated in relation to the strongly foliated phyllite.
The quartz-mica phyllite is reddish-gray and splintery, with smooth, shiny surfaces created by the abundance of micas and can locally be thin-bedded in outcrop. In most exposures the phyllite lacks recognizable bedding due to the strong component of foliation sub-parallel to bedding. The lateral extent of the phyllite unit appears to be fairly continuous occurring around more competent beds.

In thin-section, the phyllite consists predominantly of an argillaceous white mica and chlorite matrix, with only minor amounts of actinolite, all of metamorphic origin (Appendix A, #3-17-1). Detrital grains within the matrix consist predominantly of quartz ranging in size from silt to very fine sand and are usually angular to subangular. Also present are trace amounts of silt-size detrital sphene. The white mica and chlorite show a well-developed preferred orientation and are only rarely associated with tabular pleochroic biotite flakes which are slightly altered and show a preferred orientation similar to the surrounding matrix (Appendix A, #3-16-2). Where present, actinolite occurs in radiating rosettes, cross-cutting the surrounding matrix and detrital quartz grains which may indicate it was the final mineral formed during metamorphism. Also
present is a small component of cryptocrystalline epidote disseminated throughout the matrix, also of metamorphic origin.

The intervals of bedded chert interlayered with the phyllite range in thickness from 5 to 20 m and are only weakly foliated. The bedded chert is locally thin-bedded and finely-laminated with sizes ranging from 3 to 6 cm and shows pinch and swell structures due to boudinage (Figure 2). These rocks weather from reddish-brown to brownish-black, but are invariably black on broken surfaces. The bedded chert occurs mostly at the base of the unit in Arroyo Calamajué canyon. Metamorphism can tend to obscure most bedding features. In the southeastern part of the unit chert lenses occur higher up in the section where bedding characteristics are lost and thicknesses of the chert intervals are greatly reduced. The chert lenses are usually less than 4 m in thickness and cannot be traced laterally for great distances. This may be due to boudining concurrent with metamorphism.

Thin-sections of the chert show the rocks to consist primarily of cryptocrystallized to silt-sized quartz with total recrystallization, in cross-cutting patterns, to silt-sized quartz (Appendix A, §3-17-3,
Figure 2. Outcrop of basal bedded chert from unit A showing boudinage structure within Arroyo Calamajué canyon.
Some hematite occurs in the chert as cubic grains and patches forming presumably after pyrite. Carbonaceous matter up to 3% occurs as aphanitic opaque material disseminated throughout the thin-section.

Near the top of the lenticular chert unit, an increase of white mica suggests an increase in hemipelagic mud relative to silica (Appendix A, #3-17-2).

Within the top 20 to 30 m of unit A grain size coarsens to a coarse-grained chert litharenite. This sandstone is poorly-sorted and subangular, containing predominantly coarse sand-size chert and polycrystalline quartz grains with a lesser component of medium to fine sand-size feldspar grains. The feldspar consists of detrital grains of microcline and plagioclase (Appendix A, #Ma-2). Some graded bedding is present but the nature of the grading is usually obscured due to poor outcrop and metamorphism.

At the top of unit A in Arroyo Calamajué canyon, a 6 m thick by 15 m wide limestone lens is overlain by the chert litharenite. The limestone unit is interbedded with the chert litharenite within a 1 m interval and the ratio of sandstone to limestone increases upsection. Cobble size clasts of the limestone are also incorporated within the overlying sandstone, and
both size and abundance decrease as the distance from the underlying limestone increases, delineating an important facing indicator (Figure 3).

Intervals of massive, dark gray limestone interbedded with the phyllite and chert litharenite occur within the top 50 m of unit A. These intervals are generally 3 to 5 m thick and tend to lack bedding characteristics. These intervals locally contain crinoid columnals (Appendix B, fossil locality #317-3).

In thin-section, the limestone consists of predominantly very finely to finely crystalline calcite with varying amounts of recrystallized calcite giving a partial mosaic texture. Relict detrital quartz grains vary from 1 to 15 percent and are usually well-sorted and well-rounded and range in size from silt to medium sand. Fossils present in the limestone include crinoid ossicles, echinoderm plates and spines, and conodonts discussed in Chapter 3.

A few fossils, which are possibly poorly preserved solitary corals occur 5 m from the top of unit A within the limestone lens (Appendix B, fossil locality #414-5). No attempt was made for identification of fossils other than conodonts due to their poor preservation and the excellent conodont microfossil control at the top of
Figure 3: Outcrop of chert litharenite overlying a limestone lens within Arroyo Calamajué canyon showing an excellent facing indicator of cobble size clasts of limestone incorporated into the overlying sandstone.
unit A (Chapter 3, this study).

A four meter thick pebble and granule conglomerate bed occurring 30 m from the top of the unit, is designated as a marker bed on Plate I. It shows strong effects of boudinage (Plate I, symbol -o-o-o-). The pebble and granule size clasts are well-rounded and moderately well-sorted and tend to have a low sphericity. The clasts consist of metaquartzite and chert fragments. Detrital quartz grains are poorly-sorted. The medium-grained quartz shows strong undulatory extinction. The rock is highly fractured and the fractures are filled with secondary calcite and hematite (Appendix A, sample #Ma-3).

**Depositional Environments**

Metamorphism and deformation have destroyed many sedimentary features necessary for interpretation of depositional environments of unit A. Consequently, the interpretations presented are limited.

The protolith of the metachert is interpreted from the following field and petrographic characteristics: (1) absence of tractional sedimentary structures; (2) presence of equidimensional recrystallized quartz; (3) absence of obvious detrital grains; (4) aphanitic appearance in outcrop; (5) amalgamation of very thin,
laterally continuous laminae; (6) splintery fracture; (7) extreme hardness; and (8) lack of heavy minerals typical of clastic rocks. These features suggest a bedded chert protolith.

Primary chert usually forms in two ways, either by the accumulation of microscopic siliceous tests or by the inorganic precipitation of silica (Blatt, et al., 1980). Unfortunately, metamorphism has erased internal textures and left only secondary or replacement chert.

Protolith for the quartz-mica phyllite is interpreted using the following features: (1) presence of thin-bedded, argillaceous layers; (2) ratios of silt-size quartz to micaceous material; (3) lack of tractional sedimentary structures; and (4) micaceous partings between beds. These features and compositions suggest deposition of a silty claystone (Picard, 1971). The minor amounts of biotite crystals were probably derived through the recrystallization of ferro-magnesium-rich clay during metamorphism.

The coarse-grained chert litharenite has a moderate proportion of feldspar, particularly microcline, which is indicative of siliceous plutonic rocks. This grain type, which is not represented lower in the unit, may represent the tapping of a siliceous plutonic source.
A large proportion of chert fragments of pebble to granule size are present and indicate the protolith to be a chert litharenite. This may indicate an uplifted sedimentary basin that was shedding chert clasts.

The overall nature of the unit tends to be a coarsening-upward sequence going from phyllite and bedded chert intervals at the base to phyllite and minor lenticular chert higher in the unit, and finally to the introduction of a coarse-grained chert litharenite, pebbly conglomerate and limestone within the upper 20 to 30 m.

The phyllite and bedded chert at the base of the section may represent slow sedimentation rates, due to either a starved basin where continental terriginous sediments were being excluded or a moderately deep to deep water environment removed from the continental margin. The lack of siliceous tests limits interpretation of the bedded chert.

The increase ratio of phyllite to chert higher in the unit may represent a greater influx of terriginous material and increase sedimentation rates.

The top of the unit has a dramatic change of grain size and the introduction of graded bedding. This may represent a change from hemi-pelagic deposition to that
of current sand transport in an environment with submarine turbidite fan systems from a continental source. The continental source is suggested by the microcline component in the chert litharenite. The presence of limestone beds within this increased grain size may indicate a shallowing of water depth, but the lack of sedimentary structures limits interpretation. The limestone may also be a detrital, base of slope deposit.

UNIT B

Description

The metamorphosed volcanic rocks of unit B have an approximate measured thickness of 2,300 m. This unit is generally a resistant ridge former and tends to thicken to the northwest where it has a minimum thickness of 3,000 m before being intruded at the base by granodiorite of the Peninsular Ranges Batholith. The unit is generally in contact at its base with these plutonic rocks and is only in contact with the underlying sedimentary rocks of unit A at the southwestern part of the study area. The contact is poorly defined and gradational in nature. Due to poor exposure the basal contact of unit B is at best defined to a 1.5 m
interval with the underlying sedimentary rocks of unit A.

The volcanic rocks of unit B consist of intercalated basalt, hornblende andesite, and dacite submarine flows, with an increase in silica content upsection. Compositional differences between the basalt, andesite and dacite were distinguished in outcrop by their phenocryst assemblage and color. Basalt appears green in outcrop and contains coarse-grained phenocrysts of pyroxene and occurs primarily at the base of the unit. Andesite appears brown and can contain phenocrysts of hornblende whereas the dacite appears gray due to the presence of quartz and lack of actinolite and chlorite. Recognition was accomplished primarily by microscopic means (Appendix A).

The volcanic rocks of unit B were deposited as submarine lava flows, at least at the base, as indicated by thinly-laminated marine limestones surrounded by vesicular andesites and basalts (Figure 4), but individual flows are usually not distinguishable. The unit is only weakly foliated and only near the top does it show the effects of shear cleavage.

In thin-section, the vesicles are rimmed by blue-green amphibole and chlorite and are filled with
Figure 4. Outcrop of limestone surrounded by volcanics near the base of unit B in Arroyo Calamajué canyon.

Figure 5. Photomicrograph of vesicle in volcanic rock rimmed with actinolite and chlorite and filled with calcite. Sample #3-15-2, plain light, (x5).
calcite. This may indicate an order of filling from blue-green amphibole and chlorite to calcite. The vesicles range in size from 2 to 5 mm and are generally spherical in shape (Figure 5) (Appendix A, #3-15-2).

The phenocrysts consist of plagioclase, clinopyroxene (augite?) and iron oxides in the basalts, plagioclase (+ hornblende) and skeletal magnetite-ilmenite in the andesites and plagioclase and quartz in the dacites. The phenocrysts of plagioclase are usually fine- to medium-grained with clinopyroxene grains ranging up to coarse-grained. The metamorphically recrystallized plagioclases range in composition from albite to oligoclase with identification only possible where alteration has not affected twinning. The plagioclase is generally altered to finely divided aggregates of white mica, epidote, and albite, and it is notable that the centers of the crystals are more affected than the edges. Chlorite and calcite are other alteration phases in the phenocrysts. Some phenocrysts show curved twin lamellae caused by deformation.

The matrix of the basalts, andesites and dacites ranges from cryptocrystalline to very fine-grained with the original glassy matrix completely recrystallized to
albite, quartz, epidote, hematite, white mica, and chlorite. Chlorite is usually associated with the alteration and recrystallization of the phenocrysts and matrix and by the filling of cracks in plagioclase grains (Figure 6). Quartz and albite are common reactants and products in association with the formation of chlorite and are seen as equidimensional, very fine-grained secondary intergrowths that can be distinguished from each other by the inclusions present in albite. Epidote is also present as an alteration product within the matrix, occurring as nondescript masses.

In one sample garnets are associated with chlorite, white mica and albite, and cluster around relict phenocrysts of plagioclase. Since they are associated with lower greenschist minerals (discussion on metamorphism in Chapter 5) they are probably a product of hydrothermal alteration. Deer, et al., (1975) describes grossular garnet as being common in rocks which have undergone calcium metasomatism.

A 200 m long and 50 m wide lens in the northwest part of unit B consists of an andesite boulder conglomerate and is designated as subunit b₂ (Plate I). The subunit is clast-supported with the clasts being well-rounded and having low sphericity. They
Figure 6. Photomicrograph of fractured plagioclase phenocryst filled with vermicular chlorite and altered to albite. Sample #4-14-2, plain light, (x5).
show similar metamorphic alterations to the surrounding volcanic rocks with the matrix being completely altered to white mica, chlorite and hematite. The subunit probably represents a short, localized period of erosion from the volcanic edifice with the stratigraphic position being approximately in the middle of unit B.

**Depositional Environments**

Depositional environmental indicators are rare in the volcanic sequence; thus, interpretation is limited.

The presence of limestone lenses at the base of the volcanic sequence indicates that the lower part of the unit was deposited in a submarine environment. Vesicles are also common in marine volcanic flow sequences which may have been filled with gaseous phases but are now filled with calcite.

The thicknesses involved for the accumulation of at least 2,300 m of volcanic rock may indicate a close proximity to the volcanic vent since the flows themselves would coalesce quickly in a marine environment. Pillow structures were not recognized in the area and no facing indicators were seen in the vesicular volcanics.
UNIT C

Description

Unit C is lithologically a highly variable unit ranging in thickness from 300 to 400 m. It has a gradational basal contact with the underlying volcanic flow rocks of unit B and a sharp upper contact with the thin-bedded phyllites of unit D. The lithologies vary from dacite to rhyolite lithic tuffs, volcaniclastic sediments, pebbly mudstone, and pebble conglomerate. Lateral variations occur within this unit and beds usually can not be traced for great distances. The unit is generally a ridge former compared with the overlying phyllites of unit D, with a large vertical face designating the contact between these two units.

The volcanic tuffs range in composition from dacite to rhyolite and range up to 50 m in thickness and appears pale green and silver. They generally have a well-developed bedding alignment in outcrop created by lithic fragments and can also appear brecciated. In thin-section, the parallel alignment of plagioclase laths is common and generally is associated with the parallel alignment of metamorphic white micas (Figure 7). This may either be due to flowage of the tuff bed, air fall orientation, or compaction due to deformation.
Figure 7. Photomicrograph of parallel alignment of feldspar phenocrysts and white mica matrix in volcanic tuff from unit C. Sample #1-17-2, x polars, (x5).
Quartz and albite are common metamorphic alteration products of both the phenocryst assemblage and matrix.

The volcaniclastic sediments of unit C are very poorly-sorted with clasts ranging in size from granules to boulders 0.5 m in diameter. They are very angular and show graded bedding. The clasts are of a volcanic composition ranging from basalt to rhyolite and appear green to black.

Closely associated with the volcaniclastic sediments are 10 to 25 m thick sequences of pebbly mudstone and chert and metaquartzite pebble conglomerate. The pebbly mudstones vary in color from purple to red to green and are usually a combination of two or all three colors in outcrop. In thin section, the pebble size clasts consist of well-rounded metaquartzite of quartz arenite composition with low sphericity and range from 5 to 20% of the total rock. The remaining 80 to 95% of the rock is composed of a fine-grained matrix of predominantly white mica, chlorite and quartz. The white mica shows a strong preferred orientation and the quartz is probably a secondary recrystallization product of a silica rich matrix. The pebbly mudstone may be the alteration of a clay-rich volcanic matrix incorporating pebble size
metaquartzite clasts.

The chert and metaquartzite pebble conglomerates occur as thin 5 to 10 m thick beds near the top of unit C. The clasts are usually well-rounded and well-sorted with the beds being clast-supported.

A clast-supported metaquartzite boulder conglomerate occurs near the top of Units B and C and was mapped as subunit b₁. It appears bright orange to yellowish-orange due to intense hydrothermal alteration of sulphides in the matrix, creating a reddish-orange coating on the clasts. Clasts consist of metaquartzite boulders of quartz arenite composition, extremely poorly-sorted, and well-rounded (Figure 8). The quartz grain contacts within the clasts show convex-concave or lobate boundaries. The matrix is completely altered to quartz, white mica, calcite, and hematite, with the latter producing the variable red colors. The matrix also contains poorly-sorted relict detrital quartz grains (Appendix A, #2-22-1, #3-22-1).

The subunit forms large lens-shaped channels ranging up to 600 m long and 250 m wide. The source may be from uplifted metaquartzite terranes being eroded into possibly a steep slope basin forming a few large channels containing poorly-sorted boulder size
Figure 8. Outcrop of metaquartzite boulder conglomerate showing bright orange hydrothermally altered matrix from Arroyo Calamajué canyon.
Depositional Environments

The volcanic tuffs within unit C are the most silicic in composition within the island-arc sequence of units B and C and occur at the top of the volcanic sequence.

The volcaniclastic sediments with abundant basic to intermediate volcanic clasts represent the erosion of a nearby volcanic edifice where thick sequences of highly variable angular clast sizes may indicate close proximity to the volcanic source.

The pebbly mudstones may represent debris flow deposits where rapid deposition within probably steep slope basins created highly chaotic units.

The chert and metaquartzite pebble conglomerates within unit C and the metaquartzite boulder conglomerate (subunit b₁) may represent a second source terrane from an uplifted chert and metaquartzite source depositing pebble to boulder size clasts. No directional sedimentary structures were observed within this unit, but a lack of mixing between the volcanic and sedimentary source is apparent.
UNITS D AND F

Description

Units D and F comprise the upper 2,000 m of the stratigraphic section with the 300 to 400 m thick highly deformed basic volcanics of unit E occurring between them. Each unit shows approximately 1,000 m of apparent thickness in Arroyo Calamajué canyon, however the top of unit F is covered by Quaternary alluvium and was not observed. The base of unit D is at a sharp depositional contact with the underlying volcanics, volcanioclastic sediments, and pebble conglomerates and mudstones of unit C. Unit D is thinnest in Arroyo Calamajué canyon and tends to thicken to the northwest. The thinning of the phyllite to the east may be due to greater tectonic attenuation. Units D and F are characterized by very thin-bedded mica-quartz phyllite containing widely spaced interbeds of metamorphosed limestone.

As float, the phyllite is dark gray and white, highly fissile, with smooth, shiny surfaces. In outcrop, the phyllite is very thinly-bedded, with alternating dark gray to black layers, and light gray to chalky white layers (Figure 9). Beds range from .25 to 3 cm and appear to be laterally continuous with the
Figure 9. Outcrop of phyllite from unit F showing light and dark layering with pervasive shear cleavage parallel to bedding within Arroyo Calamajué canyon.

Figure 10. Photomicrograph of graded bedding in darker layers of phyllite. Sample #1-18-1, x polars, (x5).
boundary between light and dark layers well defined.

The phyllite consists predominantly of silt-size quartz in both light and dark layers. Darker layers contain high concentrations of both minute opaque particles of carbonaceous material and white mica crystals with the latter showing a strong preferred orientation. White mica and carbonaceous material are rarely seen in the lighter layers, with the latter giving the black color to the darker layers. Secondary hematite occurs in distinct layers and patches giving a red-brown, stained, patchy look to darker layers in outcrop. Granoblastic polygonal textures predominate, with both quartz and micas being locally graded within the darker layers (Figure 10) (Appendix A, §1-18-1).

The metamorphosed intervals of massive limestone, interbedded with the phyllite, range from 3 to 5 m in thickness. The limestone appears dark gray in outcrop and lacks bedding. The intervals are widely spaced within the phyllite and are laterally continuous.

In thin-section, the limestone consists of very finely crystalline calcite with minor mosaic textures resulting from recrystallization of calcite. Detrital silt-size quartz grains, up to 7%, are subangular and well-sorted, occurring locally in distinct layers.
However, in the eastern part of unit F a 3 to 5 m thick pink, sandy, limestone bed contains up to 40% detrital quartz grains. The quartz has a bimodal size distribution and is predominantly very fine-grained and subangular and moderately well-sorted. The less abundant, coarse, sand-size is well-rounded and well-sorted.

Crinoid columnals were found in a three meter thick massive sandy limestone within unit D in the canyon of Tinaja de los Frailes (Appendix B, fossil locality #415-3). Approximately five pounds of this rock was dissolved, but no microfossils were found. However, conodonts were recovered from another limestone bed within unit D (Appendix B, fossil locality #318-1) (see Chapter 3).

Laterally continuous, 3 to 6 m thick, massive two-mica phyllite occurs in northwestern exposures of unit D. They consist of subequal amounts of fine-grained quartz and medium-grained mica. The micas consist of intergrown tabular, euhedral, muscovite and biotite showing a strong preferred orientation (Appendix A, #1-21-3). The biotite and muscovite assemblage only occurs near the contact with the intrusive granodiorite. Also in the northwestern exposures of unit D are
massive, black, carbon-rich siltstones. The detrital grains consist of silt-sized quartz showing sutured boundaries with no appreciable increase in grain size due to metamorphism (Appendix A, #1-21-1).

Depositional Environments

Rocks of units D and F from the Mision Calamajué area may be interpreted as low density turbidites with widely spaced intervals of interbedded limestone. Turbidites of the low-density type generally carry clay and silt-size particles. Characteristics of low density turbidites are: (1) delicate laminations (Bouma division D) at their base; (2) grading; and (3) homogeneous layers containing virtually no sand-size particles (Rupke and Stanley, 1974).

Characteristics of the mica-quartz phyllite of units D and F suggesting deposition as low density turbidites are: (1) very thinly-bedded layers; (2) clay and silt-size sediments; (3) laminations within lighter layers; and (4) homogeneous fine-grained layers lacking sand-sized particles. The concentration of carbonaceous material in darker layers may have resulted from suspension settling of organic material between turbidite flows.

These rocks were deposited in a low energy marine
environment. The predominance of silt-sized quartz associated with white mica and organic matter suggest a clayey siltstone protolith (Picard, 1971). The presence of carbonaceous matter in the darker layers may indicate an anoxic environment of deposition.

UNIT E

Description

Unit E is a highly mylonitized unit derived from a bright green basic volcanic rock occurring between the thinly-bedded phyllites of units D and F (Figure 11). It has a maximum thickness of 500 m in the eastern part of the study area and is thinnest to the northwest where it is only 150 m thick. It has a curvilinear trend and seems to cross-cut the surrounding structural and stratigraphic patterns of units D and F in the northwest part of the unit. This highly foliated, ductilely-sheared basic volcanic or hypabyssal rock seems to be interfingered with the surrounding phyllites. The upper and lower contacts of the mylonite are gradational over a 1.5 m interval (Figure 12).

In thin-section the mylonite has an augen fabric formed by albitized plagioclase phenocrysts being
Figure 11. View to the northwest from C. El Volcancito showing the contact between the bright green mylonite of unit E and the overlying gray phyllite of unit F.

Figure 12. Outcrop of the upper contact of the mylonite of unit E and the phyllite of unit F within Arroyo Calamajué canyon.
partially or completely granulated to a microbrecciated fabric. Most notable are bent cleavage and twin planes within the calcite and albite phenocrysts within a chlorite and quartz matrix (Figure 13). Albitized plagioclase phenocrysts, if not completely granulated, show rotations within an augen fabric (Figure 14). However, the plagioclase phenocrysts are predominantly brecciated and recrystallized to a pervasive augen fabric.

Since the unit is so deformed, identification of original fabric is virtually impossible. However, the unit was probably a porphyritic, medium-grained basic volcanic or hypabyssal unit.

Whether the unit was part of the original stratigraphic sequence and subsequently mylonitized or structurally emplaced into the area and thus not part of the original stratigraphic sequence was only partially solved. Structural evidence of a cross-cutting relationship suggests the latter hypothesis, but a more complete analysis on the folding and mylonitization should be undertaken (see Chapter 4).
Figure 13. Photomicrograph of bent twin lamellae within a calcite grain in a chlorite and albite matrix. Sample #Md-10, plain light, (x5).

Figure 14. Photomicrograph of rotated albitized plagioclase phenocryst showing chlorite tails in an augen fabric. Sample #Md-12, plain light, (x5).
CHAPTER 3

FOSSILS AND AGE

UNIT A

Fossils

Fossils from unit A in the Mision Calamajué area occur exclusively in metamorphosed limestone beds within the top 25 m of the unit. Fossils include crinoid columnals and solitary corals which are poorly preserved and conodonts which are moderately well preserved in these limestone beds.

Conodonts recovered from unit A have been identified by Dr. Richard Miller at San Diego State University as Gnathodus bilineatus (Roundy), Gnathodus inornatus (Hass) (Appendix B, fossil locality #317-3). Other indentifications that have been made on fragmentary conodont genera include Hindeodella, Neoprioniodus, Falcodus and Prioniodus (Figures 15 and 16). These conodonts occur in a three meter thick massive limestone bed, 15 m below the top of unit A.

Gnathodus bilineatus (Roundy) in association with three other species defines three biozones in the Early Chesterian. These other species are Cavusgnathus charactus (Rexroad) for zone 1, Cavusgnathus altus
Figure 15. Conodonts of unit A, *Gnathodus bilineatus* (Roundy), *Gnathodus inornatus* (Hass). Magnification x40.

Figure 16. Conodont genera of unit A, *Hindeodella*, *Neoprioniodus*, *Falcodus*, and *Prioniodus*. Magnification x40.
(Rexroad) for zone 2, and *Kladognathus mehli* (Rexroad) for zone 3. *Gnathodus bilineatus* (Roundy) was not seen in association with these three other species. The type section for these species in the Early Chesterian is the Ste. Genevieve through Glen Dean Formations in the Illinois Basin (Collinson, et al., 1971).

The presence of *Gnathodus bilineatus* (Roundy) limits this 3 m limestone bed identification to the Early Chesterian. The Meramecian-Chesterian boundary is defined by the basal occurrence of *Gnathodus bilineatus* (Roundy) within the Ste. Genevieve Formation in the Illinois Basin 339 Ma (Harland, et al., 1982).

The occurrence of *Gnathodus bilineatus* (Roundy) defines a 9 Ma interval in the Early Chesterian in North America and correlates to the Brigantian and Pendleian Series in Western Europe (Harland, et al., 1982).

*Gnathodus bilineatus* (Roundy) is a diagnostic species for age determination in both North America and western Europe. There tends to be a lack of provinciality in the Upper Mississippian as evidenced by their occurrence in both continents which may be due to the suturing of western Europe and North America during the Carboniferous (Smith et al., 1981).
This interval only defines the time limits of deposition for this three meter thick limestone bed in the uppermost part of unit A. This gives a maximum age for the overlying andesitic volcanic rocks of unit B and may define approximate initiation of andesitic flow material due to close proximity stratigraphically of the limestone bed to the overlying volcanic rocks. The *Gnathodus bilineatus* (Roundy) fossils were probably not reworked due to their abundance and lack of fragmentation.

**UNIT D**

**Fossils**

Fragmentary conodonts were recovered from a metamorphosed limestone bed in unit D in the northwestern part of the study area (Appendix B, fossil locality #318-1). A tentative Carboniferous age was assigned to these conodonts by Dr. Richard Miller (personal communication, 1984), due to their fragmentary nature, no better identification could be attempted. Since these conodonts overlie the island-arc sequence of units B and C a Carboniferous age can be assigned to all of the underlying volcanic strata.

The conodonts of unit D were probably not reworked
outside of the Carboniferous. This is suggested by a Pb/Pb minimum age of 262 Ma from the underlying island-arc sequence (Appendix C). This is consistent with the conodonts found in unit D.
CHAPTER 4

STRUCTURE

The Carboniferous rocks of Mision Calamajué have a northwest-striking and steeply northeast-dipping planal orientation within the 21 km long and 9 km wide study area (Plate I). Units A through F are exposed across the measured section of Arroyo Calamajué with the basal unit A to the southeast and unit F at the top of the section to the northeast. Overturned sections are believed to be minimal and no major repetition of the section has been recognized. Small isoclinal folds disrupt the dominant northwesterly strike of the area, and just east of the study area an abrupt, northeasterly bend in the homocline is visible on aerial photographs. This bend may be the nose of a large northwest-striking isoclinal fold with the homocline representing the right-side-up south-westerly limb. However, this feature may also be explained as a large-scale drag fold created by movement on the Gonzaga lineament truncating the upper units of Mision Calamajué and may indicate a sinistral component of motion for this feature.

Small-scale isoclinal folding is seen in Mision
Calamajué and is best recognized in the very thin-bedded phyllites of units D and F where differences in compositional layering best define the scale and extent of the folds. The small scale folds are extremely rare and wavelengths can range up to 0.5 m in size. Deformation which produced these small scale folds was sufficiently intense to cause flowage of the more ductile beds, producing pinch and swell, and locally boudinage within the quartz-mica phyllites and bedded cherts of unit A. On the average the fold axes strike and plunge to the northwest, parallel to the surrounding structure, but since these folds are rare and shear foliation generally obscures the isoclinal folds, the fold axes are poorly understood. The widely-spaced limestone beds within unit F do not show this small-scale isoclinal folding, but just east of the area in the nose of the large fold the limestone beds show these features on the scale of a few meters (Gastil, oral communication, 1984).

Associated with the isoclinal folding is a well-developed shear cleavage that parallels the axial plane foliation within units D and F. Bedding commonly parallels the axial plane foliation, but where foliation crosses the bedding, so does shear cleavage.
Essentially there has been the development of shear cleavage within the phyllite units where small striae have developed along each bedding surface. These striae and associated crenulations are best recognized within the very thin-bedded phyllites of units D and F.

**FOLIATION**

The pre-batholithic rocks have a well-developed northwest-southeast foliation that dips steeply northeast. The strike of foliation rarely varies more than a few degrees from the strike of bedding which is approximately N60°W, with dips ranging from 60°NE to nearly vertical. The foliation is best recognized in the very thin- to thinly-bedded phyllites. The highly foliated rocks are best described as phyllite, as the rock has not been metamorphosed to a degree where the term schistosity is warranted.

**Timing**

The foliation post-dates the intrusion of gabbroic rocks as they are foliated parallel to the surrounding structure, but pre-dates or accompanies the intrusion of the unfoliated granodiorites of the Peninsular Ranges Batholith. The possible age of the foliated gabbroic rocks will be discussed in relation to metamorphism in
Chapter 5. Foliation may also post-date or accompany the large isoclinal fold or drag fold just to the east of the study area as the northwesterly axial plane foliation cuts across bedding (Gastil, oral communication, 1984).

The age of tilting for the homoclinal strata associated with the large-scale isoclinal folding is poorly bracketed, it post-dates the Carboniferous rocks and pre-dates the granodiorite intrusion.

**FAULTING AND SLICKENSIDES**

Faulting within the Mision Calamajué area is difficult to detect because of the shear cleavage present in the rocks and the lack of stratigraphic variation within certain units. Faults which offset contacts and marker beds were located and mapped but are rare in the study area (Plate I).

Minor slickensides appear to have developed in association with hydrothermal alteration. This is seen just above the hydrothermally altered metaquartzite boulder conglomerate (subunit b₁) in Arroyo Calamajué, within a green metaquartzite pebbly mudstone. Here, small fault striated surfaces seemingly occur with little relation to direction along
a complete network of fractures.

**MYLONITES**

The mafic volcanic rocks of unit E have undergone extreme ductile deformation, forming a microbrecciated fabric containing flow textures. Rocks that have been mylonitized due to mechanical forces applied in definite directions undergo recrystallization. The formation of a fine-grained augen fabric from the recrystallization of the plagioclase phenocrysts is only apparent under the microscope. Bent cleavage and twin lamellae in calcite and quartz grains are seen in thin section (Figure 13). Also, rotated plagioclase phenocrysts are seen within a smeared chlorite and albite matrix (Figure 14).

The age and direction of the mylonitization of unit E is uncertain, but field relations suggest that mylonitization post-dated the intrusion of the gabbroic rocks as they are foliated along the margins with the foliation possible being contemporaneous with mylonitization.
CHAPTER 5

METAMORPHISM

INTRODUCTION

The mineral assemblages and metamorphic textures of the Carboniferous rocks in the Mision Calamajué area are indicative of a regional dynamothermal metamorphic event plus hydrothermal alteration, and possible contact metamorphic overprint. Recrystallization is evident in virtually all rocks, but the crystallization of specific metamorphic minerals is dependent on the bulk composition of the host rock.

The first part of this chapter discusses the metamorphic mineral association of rocks in which the crystallization of new minerals provides an indication of the physical conditions of metamorphic pressure and temperature. The latter part of this chapter discusses the hydrothermal alteration and possible contact metamorphic overprint in the Mision Calamajué area.

METAMORPHIC MINERAL ASSOCIATIONS

Meta-Pelites

The meta-pelites containing porphyroblasts which provide an indication of the physical conditions of
metamorphism are the actinolite bearing phyllites. The mineral assemblage of quartz, white mica and chlorite does not provide a unique indicator for the grade of metamorphism since the minerals occur over a wide range of pressures and temperatures, but the porphyroblasts of actinolite indicate lower greenschist grade metamorphism. The mineral assemblage observed in these rocks is:

Quartz + White Mica + Chlorite + Actinolite

The quartz is of detrital origin and no increase in grain size has occurred, only the contacts between individual grains have been affected and are now curved or sutured in nature. The white mica may be the recrystallization product from an original clayey matrix, but part may be of detrital origin. Due to their minute crystal size no textural relations between these two white micas could be determined.

Chlorite forms under metamorphic as well as under diagenetic conditions, and is a stable constituent in sediments as well as in metamorphic rocks, but vermicular and penninite chlorite are common chlorite minerals in rocks that have experienced lower greenschist grade metamorphism.
Metavolcanic Rocks

The metavolcanic rocks of the Mision Calamajué area contain a distinct mineral assemblage which enables an estimation of metamorphic pressure and temperature. The mineral assemblage in the rocks of units B and C include:

Albite + White Mica + Chlorite + Epidote + Quartz + Actinolite

These minerals are the metamorphic alteration products of the phenocrysts and matrix in the porphyritic volcanic rocks. The phenocrysts tend to be altered and filled with albite, white mica, epidote and calcite, with the matrix being completely altered to epidote, chlorite, quartz and white mica.

CONDITIONS OF METAMORPHISM

In recognized metamorphic progressions from very-low grade to low grade metamorphism, the loss of prehnite and pumpellyite and the occurrence of iron-poor epidote like zoisite and clinozoisite plus actinolite designates this transition (Winkler, 1979). Neither prehnite nor pumpellyite were recognized in the volcanic rocks and the presence of actinolite with iron-rich epidote and minor amounts of iron-poor epidote is apparent. Metamorphic zone progressions
recognized in the Tanzawa Mountains in Japan as well as places in New Zealand, the western European Alps and the Kii Peninsula of Japan show a transition from very-low grade to low grade metamorphism with a lack of iron-poor epidote (Winkler, 1979). These low grade metamorphic terranes contain a mineral assemblage similar to the rocks of Mision Calamajué. These terranes have experienced very low to normal geothermal gradients and experienced lower greenschist grade metamorphism suggesting a lower pressure range for the metamorphism in the Mision Calamajué area.

The metamorphic temperature range for the mafic and pelitic rocks of the Mision Calamajué area with their associated mineral assemblages is 350°C for the lower boundary with very-low grade, and 425°C for the upper boundary where biotite is stable in pelitic rocks representing the temperature range for lower greenschist grade metamorphism (Figure 17).

**TIMING OF METAMORPHISM**

The timing of metamorphism for the Carboniferous rocks of Mision Calamajué is poorly controlled. It is possible that it is of Late Cretaceous age and related to emplacement of the Peninsular Ranges Batholith. K/Ar
Figure 17. Pressure-temperature diagram, showing lower greenschist stability field of mineral assemblage in rocks of the Mision Calamajué area (shaded region) (from Winkler, 1979).
cooling ages ranging from $107.5 \pm 3.0$ Ma to $62.6 \pm 1.5$ Ma were determined for plutonic rocks from the Peninsular Ranges Batholith indicating a Late Cretaceous age of emplacement (Gastil and others, 1975). It is unknown whether the granodiorites in the study area are contemporaneous with the Upper Cretaceous granodiorites in the Peninsular Ranges Batholith. It is also possible that the plutons are of Carboniferous age and related to the island-arc sequence in the area. But this seems unlikely as they would probably be metamorphosed to lower greenschist grade like the surrounding Carboniferous rocks and gabbroic rocks in the study area.

HYDROTHERMAL ALTERATION

Strong hydrothermal alteration has effected the rocks of the study area and is best observed within Arroyo Calamajué canyon where locally altered volcanic and sedimentary rocks of units B and C are exposed. This alteration is probably continuing at depth as evidenced by the warm carbonate and sulfate spring activity. The matrix within subunit b₁ is bright orange and is diagnostic for this metaquartzite boulder conglomerate. The emplacement of pyrite is common
within the surrounding volcanics of unit B near the contact of subunit b₁. Thus, subunit b₁ may have acted as a conduit for hydrothermal fluids due to a higher permeability in relation to the surrounding volcanic rocks. The conglomerate may have been more susceptible to hot fluids running through its matrix and thus intensely altering it. The clasts of metaquartzite within the subunit seem to remain essentially unaltered. The surrounding volcanic rocks of units B and C also show the effects of this hydrothermal alteration. The age of hydrothermal alteration is poorly controlled. This event may be related to the hydrothermal alteration and mineralization taking place today, thus indicating a Tertiary to modern hydrothermal event. It is also possible that the hydrothermal alteration is in part Carboniferous, related to the cooling of the subaqueous andesite flows creating a circulation of marine waters through the overlying metaquartzite boulder conglomerate (subunit b₁) with its emplacement of pyrite and associated minerals or, the hydrothermal event could have been in part related to the emplacement of the possible Late Cretaceous granodiorites.

The spacial association of alteration with active
warm carbonate and sulfate enriched springs strongly suggests that the mineralization and thermal spring activity are related and thus indicates the Tertiary to modern event.

**CONTACT METAMORPHISM**

Contact metamorphism is best recognized in the pelitic rocks of the study area where the mineral assemblage of biotite and muscovite is seen in northwestern exposures of unit D, and in unit A near the contact of the granodiorite. This indicates minimum temperatures of formation between 425° and 475° C for the formation of intergrown biotite and muscovite (Figure 17). Crystals of andalusite are also seen within the pelitic sediments at northeastern exposures of unit F near the mouth of Arroyo Calamajué. The formation of andalusite at pressures of 4 to 6 Kb determined experimentally is 500° to 600° C (Winkler, 1979). The most distinctive occurrence of andalusite is not adjacent to exposed plutonic rock.
CHAPTER 6

LITHOLOGIC CORRELATIONS

INTRODUCTION

The volcanic rocks of Mision Calamajué are the only Paleozoic volcanic rocks of island-arc affinities that have been reported in Peninsular California (Figure 18).

Figure 19 is a generalized map showing the aerial extent of major lithostratigraphic units in the western United States for rocks of Carboniferous age. The rocks of the Klamath Mountains and Northern Sierra Nevada Mountains as well as the rocks of northwestern Washington are lithologically and chronologically similar to the rocks of Mision Calamajué.

Preserved outcrops of island-arc rocks of Carboniferous age in the western United States are very limited due to intrusion, metamorphism and eastward movement of Carboniferous rocks along the Sonoma (Golconda) thrust system (Snyder, et al., 1983).

The Carboniferous island-arc rocks in the Cordillera have a complex history related to an unstable continental margin. The beginning of the Carboniferous period is marked by the initiation of the
Figure 18. Distribution of pre-batholithic island-arc volcanic rocks in Baja California Norte (in part from Gastil and others, 1975).
Figure 19. Generalized map showing areal extent of major lithostratigraphic units in western United States during the Carboniferous (from Rich, 1977).
Antler Orogeny. The origin of the Late Devonian and Early Mississippian Antler Orogeny is much debated. Continental shelf sedimentation was first interrupted by the Antler Orogeny, when a basinal sequence of Cambrian to Late Devonian rocks was thrust eastward onto the edge of the continental shelf along the Roberts Mountain thrust (Nilsen and Stewart, 1980). Erosion of the Roberts Mountain allochthon in the Late Paleozoic shed sediments eastward into the Antler foredeep basin and westward into an inner-arc basin (Speed and Sleep, 1982). The old edge of the continental shelf, now covered by the Roberts Mountain allochthon and younger overlying sedimentary rocks, was again overridden by the Golconda allochthon during the latest Permian to Early Triassic Sonoma orogeny (Silberling and Roberts, 1962). The overall structural trend within the Antler belt is to the northeast (Miller, et al., 1984).

Figure 20 is a paleogeographic map of the western United States during the Carboniferous. The preserved Carboniferous island-arc rocks in the Klamath and Northern Sierra Nevada Mountains are lithologically most similar to the Carboniferous rocks of Mision Calamajué and thus are the most relevant to this study.
Figure 20. Paleogeographic map of western United States during the Carboniferous (from Rich, 1977).
Island-Arc Deposits

Chilliwack Group. The Lower Pennsylvanian Chilliwack Group in northwestern Washington constitutes a complex assemblage of volcanic flows, volcanioclastics, graywacke, cobble conglomerate, bedded chert and argillaceous limestone (Rich, 1977). These rocks are lithologically very similar to the rocks of the Mision Calamajué area.

Baird Formation. The Baird Formation of the Klamath Mountains has a similar age and lithology to the Chilliwack Group in northwestern Washington. It consists of a volcanic and volcaniclastic sedimentary sequence and is Pennsylvanian in age (Poole and Sandberg, 1977).

Taylor Formation. The Mississippian and Devonian Taylor Formation in the northern Sierra Nevada Mountains consists of up to 2.7 km of massively bedded tuff breccia and lapilli tuff of basaltic to basaltic andesite composition, with subordinate interbeds of finer-grained, andesitic tuffaceous sedimentary rocks. Andesitic pillow lava and pillow breccia are locally intercalated within the pile. The coarser breccia of
the Taylor is typified by blocks of clinopyroxene-plagioclase porphyry set in a dark gray-green matrix of crystal fragments and ash and lapilli sized andesitic rock fragments (Schweickert and others, 1984).

**Peale Formation.** The Pennsylvanian and Mississippian Peale Formation in the northern Sierra Nevada Mountains contains two recognized members. The lower member consists of 0-1000 m of trachytic or quartz latitic tuff, breccia, flows, and sills, with minor interbedded volcaniclastic sedimentary rocks and limestone. The upper member of the Peale consists of 250 to 500 m of chert, slate, breccia, and tuffaceous material (Schweickert and others, 1984).

**Goodhue Formation.** The Permian and Pennsylvanian Goodhue Formation crops out in the northern Sierra Nevada Mountains. It consists of up to 2.8 Km of breccia, hyalclastite, and pillow lava of basaltic to basaltic andesite composition (Durrell and D'Allura, 1977).

**TECTONIC IMPLICATIONS**

Figure 21 is an index map showing the present position of the study area in Baja California Norte in
Figure 21. Index map showing present position of Baja California and the San Andreas Fault and Sonora-Mojave Megashears I and II.
relation to the island-arc and associated rocks in the western United States. It also shows the Cenozoic right-lateral San Andreas fault system in California and two proposed left-lateral faults in Sonora, Mexico. The first left-lateral fault, the Mojave-Sonora Megashear (MSMS I), was proposed to explain the truncation of the island-arc and inner-arc basin deposits as well as offsets within miogeoclinal rocks from the Caborca terrane and the Inyo Mountains (Silver and Anderson, 1974). It is thought to have been active during the Jurassic with 700 to 800 km of left-lateral offset. Miogeoclinal rocks from the San Bernardino Mountains, west of MSMS I, complicate the hypothesis of a left-lateral fault. The miogeoclinal rocks appear west of MSMS I but are explained by Silver and Anderson as having been thrust westward across the megashear trace. The actual placement of the fault is much debated as exemplified by Dickinson's (1981) placement of MSMS I in a more easterly position in Sonora, Mexico. Dickinson (1981) actually divides the fault into strands west and east of the San Bernardino Mountains. Another megashear has been proposed, approximately parallel to the first with a similar sense of motion, 100 km to the south of MSMS I and is
called Mojave-Sonora Megashear II (MSMS II) (Silver and Anderson, 1983). It has been proposed to have up to 700 km of offset and was also active during the Jurassic. It also has been proposed to explain similar type offsets seen within miogeoclinal and cratonal rocks within the belt defined by the two sinistral fault systems.

Figure 22 introduces a palinspastic restoration for the San Andreas and the proposed proto-San Andreas fault systems which were active during the Cenozoic. 300 km of right-lateral offset was restored on the San Andreas, which was active during the last 4.5 Ma. Additionally, 135 to 425 km of offset is proposed on the proto-San Andreas which was active during the Early Tertiary and Late Cretaceous (Nilsen, 1978), and was also active along an earlier trace of the present San Andreas fault. The placement and existence of the proto-San Andreas fault is very controversial. This author chose the minimum amount of offset, 135 km, for the proto-San Andreas fault system. This juxtaposes peninsular California with the states of Sonora and Sinaloa on Mainland Mexico (Figure 22).

A second palinspastic restoration on MSMS I and MSMS II, which were active during the Jurassic, accounts
Figure 22. Palinspastic restoration for the San Andreas and proto-San Andreas fault systems juxtaposing Baja California with the states of Sonora and Sinaloa, Mexico.
for the proposed 700 to 800 km of left-lateral offset on MSMS I and up to 700 km of offset for MSMS II (Figure 23). This author used 750 km of restoration on MSMS I and 700 km of restoration on MSMS II. This is very significant because it juxtaposes the Carboniferous island-arc rocks of Mision Calamajué in Baja California Norte with the Carboniferous island-arc rocks from the Klamath Mountains and Northern Sierra Nevada Mountains. An important assumption that is inherent in this model is that everything west of MSMS I and II acted as one coherent block. This has not yet been determined within Baja California. Furthermore, it is not known whether the rocks of Mision Calamajué were part of western North America during the Carboniferous. A structural comparison between the rocks of western United States and the study area in Baja California shows that the predominant structural trend of the Antler Orogeny is to the northeast and the predominant structural trend of the Mision Calamajué rocks is to the northwest. This must be taken into account when considering the proposed model and a more complete structural analysis must be completed to determine if any previous northeast structural trends are present in the study area within a later northwest structural
Figure 23. Palinspastic restoration for the Mojave-Sonora Megashears I and II juxtaposing the island-arc rocks of Mision Calamajué and the Klamath-Northern Sierra Nevada Mountains.
overprint. It is possible that structural trends may wrap around the North American continent paralleling the cratonic edge.
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REFERENCES CITED


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APPENDICES
APPENDIX A

Petrographic Descriptions and Sample Locality Map
### Petrographic Descriptions

#### Unit A

**#3-17-1).** Quartz-mica phyllite, black, weathers light brown, cryptocrystalline to coarse silt size, thin bedded, foliated, matrix supported.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>White mica</td>
<td>(60%)</td>
<td>minute tabular crystals, some showing radiating structures, associated with clay alteration.</td>
</tr>
<tr>
<td>Quartz</td>
<td>(27%)</td>
<td>silt size detrital quartz grains, subangular, well-sorted, few grains in contact, low P.I.</td>
</tr>
<tr>
<td>Epidote</td>
<td>(10%)</td>
<td>nondescript patches of microcrystalline masses, fills interstitially between grains.</td>
</tr>
<tr>
<td>Hematite</td>
<td>(1%)</td>
<td>scattered patches filling in matrix, secondary.</td>
</tr>
<tr>
<td>Chlorite</td>
<td>(3%)</td>
<td>minute aggregates and tabular grains, secondary.</td>
</tr>
</tbody>
</table>

Protolith: **Silty Claystone**

**#3-16-2).** Mica-quartz phyllite; brownish-black, weathers light brown, coarse silt to very fine-grained, massive well-sorted, subangular, slightly foliated, grain supported.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>(57%)</td>
<td>coarse silt to very fine-grained detrital quartz, subangular, well-sorted, curved and embayed quartz boundaries.</td>
</tr>
<tr>
<td>White Mica</td>
<td>(18%)</td>
<td>minute aggregates shaped grains, showing a slight preferred orientation, micas intermixed with quartz, probably partial alteration of clay matrix.</td>
</tr>
<tr>
<td>Biotite</td>
<td>(20%)</td>
<td>pleochroic olive green to brown, tabular and prismatic flakes, slight preferred orientation, probably of detrital origin, slightly altered.</td>
</tr>
</tbody>
</table>
Epidote (5%): disseminated throughout matrix infilling between quartz and mica grains.

Protolith: Clayey Siltstone

#12-18-2E).

and


Quartz-mica Matrix (81%): predominantly cryptocrystalline recrystallized silica intermixed with white mica.

Quartz (15%): relict detrital grains, medium grain size, well-rounded and sorted, predominantly monocrystalline with minor polycrystalline quartz.

Recrystallized Silica (3%): pore filling, secondary.

Iron Staining (1%): hematite occurring along crystal boundaries.

Protolith: Sandy Clayey Siltstone

#Ma-2). Chert Meta-litharantite: brownish-black, weathers dark brown, poorly-sorted, moderately well-rounded, coarse-grained.

Quartz (25%): predominantly Qtm showing undulose extinction, coarse-grained, poorly-sorted, highly fractured. Some Beta quartz present showing embayments.

Microcline (3%): medium to fine-grained, well-rounded, microcline twinning present.

Hematite (6%): disseminated in layers within matrix, secondary.

Siliceous Matrix (61%): recrystallized silica from a previous chert fragment rich matrix, cryptocrystalline.
Plagioclase (5%): detrital grains showing carlsbad-albite twinning. Twin lamellae show bent cleavage planes caused by distortion. Medium-grained.

Iron Oxides (1%): relict detrital heavy minerals, very fine-grained.

Protolith: Litharenite

Pebbly quartzite and chert conglomerate; brownish-black, weathers dark brown, extremely poorly-sorted, moderately well-rounded.

Quartzite Clasts (30%): show some elongation, well-rounded, low sphericity, some clasts show high amount of hematite alteration, pebble and granule size.

Chert Clasts (20%): subangular cryptocrystalline chert fragments, fractures being filled with secondary calcite. Pebble and granule size.

Calcite (25%): highly fractured rock filled with calcite, secondary.

Quartz (20%): subrounded detrital quartz, poorly-sorted, medium-grained, undulose extinction.

Hematite (5%): associated with calcite implantation into veins, secondary.

#12-18-1A). Fossiliferous, sandy meta-limestone; dark gray, massive, very finely crystalline, partial mosaic texture.

Calcite (84%): calcite, very finely crystalline with partial recrystallized mosaic crystals.

Quartz (13%): relict monocristalline detrital quartz grains, subrounded, fine-grained, moderately well-sorted. Poly-crystalline detrital quartz grains, well-rounded, medium-grained, some secondary silica replacement.

Iron Staining (1%): discrete layers of hematite, secondary.
Chlorite (tr.): secondary.
Calcedony (tr.): secondary.
Quartz (tr.): secondary.
Fossils Present (2%): Echinoderm plates, crinoid ossicles.

Protolith: Fossiliferous, Sandy, Crystalline Limestone

#12-18-1I). Metalimestone; dark gray, massive, finely crystalline, partial mosaic texture.
Calcite (92%): calcite, finely crystalline with partial recrystallized mosaic crystals.
Iron Oxides (5%): discrete layers and patches of hematite, secondary.
Quartz (3%): relict detrital grains, very fine-grained.

Protolith: Crystalline Limestone

#12-18-1H). Fossiliferous, sandy metalimestone; dark gray, massive, partial mosaic texture.
Calcite (86%): subequal parts of calcite and recrystallized mosaic crystals.
Quartz (9%): relict detrital grains, subrounded, moderately-sorted, medium-grained, predomately Qm with minor secondary replacement grains and patches of silica.
Fossils Present (5%): include crinoid ossicles echinoderm plates, traces of red algea.

Protolith: Fossiliferous, Sandy, Crystalline Limestone

#12-18-1G). Fossiliferous metalimestone; light blue, massive, finely crystalline, partial recrystallized mosaic texture.
Calcite (92%): calcite, finely crystalline, partial recrystallized mosaic crystals.
Quartz (6%): relict detrital grains, very fine-grained, well-sorted, subrounded. Minor secondary recrystallized silica.
Iron Oxides (1%): patchy hematite grains, secondary.
Fossils Present (1%): crynoid ossicles, echinoderm plates.

Protolith: Fossiliferous, Crystalline Limestone

#12-18-1E). Fossiliferous metalimestone; light blue, massive, finely crystalline, with partial mosaic texture.

Calcite (86%): Predominantly calcite, minor amounts of recrystallized mosaic crystals.
Quartz (6%): relict detrital grains, well-sorted, well-rounded, high sphericity, medium-grained, straight extinction.
Siliceous Quartz (1%): recrystallized silica, elongate medium grain size, pore-filling, secondary.
Hematite (3%): patches of hematite crystals, secondary.
Fossils Present (4%): include crinoid ossicles, echinoderm spines and plates, minor red algae.

Protolith: Fossiliferous, Crystalline Limestone

#12-18-1F). Metalimestone; dark gray, massive, fine-grained, partial mosaic texture.

Calcite (99%): subequal amounts of calcite and recrystallized mosaic crystals.
Quartz (1%): relict detrital grains, very fine-grained, subangular, well-sorted.
Iron Oxides (tr.): patches of hematite grains, secondary.

Protolith: Crystalline Limestone

#12-18-1J). Fossiliferous, sandy metalimestone; dark gray, massive, with recrystallized mosaic texture.

Calcite (63%): subequal amounts of calcite and recrystallized mosaic crystals.
Quartz (15%): relict detrital grains, well-rounded and sorted, medium-grained, monocrystalline.

Siliceous Quartz (15%): recrystallized, cryptocrystalline siliceous grains, pore filling, secondary.

Iron Staining (1%): hematite occurring along crystal boundaries.

Fossils Present (6%): crinoid ossicles, echinoderm plates and spines.

Protolith: Fossiliferous, Sandy, Crystalline Limestone

#3-15-3). Metalimestone; dark gray, massive, very finely crystalline, partial recrystallized mosaic texture.

Calcite (97%): predominately calcite, very finely crystalline, minor amounts of recrystallized mosaic crystals.

Hematite (3%): hematite staining surrounding recrystallized mosaic crystals and patches of disseminated grains, secondary.

Protolith: Crystalline Limestone

#3-17-4). Fossiliferous, sandy metalimestone; dark gray, very finely crystalline, massive, partial mosaic texture.

Calcite (80%): predominately calcite, very finely crystalline, minor amounts of recrystallized mosaic crystals.

Quartz (13%): relict scattered detrital grains, fine-grained, well-sorted, sub-rounded, monocrystalline.

Hematite (3%): scattered disseminated hematite staining, secondary.

White Mica (1%): minute aggregates, secondary.

Fossils Present (3%): echinoderm plates and spines, crinoid ossicles.

Protolith: Fossiliferous, Sandy, Crystalline Limestone
#3-17-2). Metachert; black, weathers reddish-brown, cryptocrystalline, lenticular, partial mosaic texture.

Siliceous

Metachert (86%): subequal amounts of cryptocrystalline grains and recrystallized mosaic texture.

White Mica (6%): minute aggregates and patches, secondary.

Carbonaceous

Material (3%): disseminated minute opaques.

Hematite (5%): cubic shaped aggregates and patches of hematite, secondary.

Protolith: Chert Lens

#3-17-3). Metachert; black, weathers reddish-brown, thinly-bedded, cryptocrystalline, partial mosaic texture.

Siliceous

Metachert (89%): cryptocrystalline with partial recrystallized mosaic crystals.

Hematite (10%): some cubic shaped grains and patches of hematite altered from pyrite, secondary.

White Mica (1%): minute aggregates, secondary

Protolith: Bedded Chert

#12-18-1K). Metachert; reddish-brown to black, cryptocrystalline, thinly-bedded, partial recrystallization to fine-grained.

Siliceous

Metachert (70%): cryptocrystalline.

Quartz (29%): recrystallized from ground mass to fine-grained cross-cutting pattern.

Hematite (1%): cubic and disseminated hematite, secondary.

Protolith: Bedded Chert
Unit B

#315-2). Meta-andesite; light gray, oxidized reddish-brown, cryptocrystalline to fine-grained, porphyritic texture, vesicular.

Matrix (66%): cryptocrystalline to very fine-grained. Original matrix completely altered.

Chlorite (40%): metamorphically formed from matrix and associated with albite. Filling and altering plagioclase.

Epidote (22%): alteration product of the volcanic matrix, metamorphic.

Albite (18%): alteration product of matrix associated with quartz.

Vermicular Chlorite (5%): alteration product of matrix, metamorphic.

Vesicles (5%): filled with secondary calcite and rimmed by chlorite and possibly actinolite.

Plagioclase (22%): relict plagioclase, highly altered and filled with chlorite, fine-grained.

Iron Oxides (4%): irregular tabular shape and needle-like crystals, highly altered.

Leucoxene (8%): alteration product of ilmenite.

Protolith: Andesite

#4-14-2). Meta-dacite; gray, weathers yellowish-brown, cryptocrystalline to fine-grained, porphyritic texture.

Matrix (53%): cryptocrystalline to very fine-grained. Original matrix completely recrystallized.

Albite (25%): replacement mineral filling fractures in matrix and phenocrysts of plagioclase. Associated with quartz.

Chlorite (20%): Early metamorphic mineral replacing plagioclase and matrix.
Quartz (8%): secondary, associated with albite.

Actinolite (12%): pleochroic green, moderate relief, inclined extinction, moderate birefringence, associated with chlorite in matrix.

Stilpnomelane (5%): pleochroic brown and yellow, filling in fracture and associated with albite, secondary.

Epidote (30%): alteration of matrix and opaque included within saussurite patches.

Plagioclase (45%): fine-grained plagioclase laths, altered and filled with chlorite.

Ilmenite (2%): minor opaques altering locally to leucoxene.

Protolith: Dacite

Meta-basalt; light gray with black phenocrysts, coarse-grained, porphyritic texture.

Matrix (29%): cryptocrystalline to very fine-grained. Original matrix completely altered to chlorite and epidote.

Chlorite (40%): alteration of matrix and filling of fractures within plagioclase. Possibly penninite.

Epidote (55%): alteration of volcanic matrix included within saussurite patches.

Hematite (5%): patches of hematite disseminated in matrix, secondary.

Plagioclase (28%): medium- to coarse-grained showing alteration to chlorite, albite and white mica.

Clino.pyroxene (36%): augite (?), coarse-grained, short prismatic habit showing strong polysynthetic twinning and herringbone structure, altered to actinolite.
Iron Oxides (7%): fine-grained opaques, probably ilmenite altering to leucoxene rims.

Protolith: Basalt

#1-20-1). and #1-20-1B). Meta-dacite: bluish-gray, weathers brown, cryptocrystalline to medium-grained, porphyritic and glomerophyritic textures.

Matrix (43%): cryptocrystalline to fine-grained, mostly altered to quartz, albite and micas.

Albite (40%): equigranular albite with curved grain boundaries, full of inclusions of possibly prehnite and white mica.

Quartz (40%): in close association with albite in matrix.

White Mica (10%): minute aggregates disseminated in matrix and some short prismatic shapes.

Epidote (10%): parallel extinction, fairly-high relief, moderate birefringence.

Iron Oxides (12%): black in reflected light, possibly magnetite or ilmenite, very little alteration, cubic or irregular fine-grained crystals.

Plagioclase (45%): medium-grained phenocrysts and fine-grained laths of andesine composition. Some laths cluster together in 2 mm patches.

Protolith: Dacite


Matrix (55%): cryptocrystalline to fine-grained. Complete alteration of matrix diagenetically and metamorphically.
Albite (23%): very fine-grained aggregates and large 5 mm alteration zones of relict crystals, associated with quartz reaction.

Stilpnomelane (12%): fine-grained prismatic crystals and micaceous masses, parallel extinction, pleochroic brown and yellow, may be hydrothermally formed.

Quartz (40%): clusters of colorless, low relief, low birefringence minerals associated with chlorite and stilpnomelane.

Chlorite (25%): secondary alteration product associated with albite.

Albite (6%): medium-grained albite crystals with opaques or other inclusions.

Plagioclase (25%): medium- to fine-grained phenocrysts altering to chlorite, epidote and stilpnomelane.

Quartz (8%): involved in albite reaction of plagioclase phenocrysts.

Iron Oxides (3%): Ilmenite (?) Some relict tabular shapes.

Leucoxene (3%): associated with ilmenite alteration, secondary.

Protolith: Dacite

Volcanic Litharenite: gray, weathers greenish-brown, shows some banding or layering in outcrop and optically, hydrothermally altered.

Matrix (79%): very fine-grained, completely recrystallized and altered.

Silica (62%): cryptocrystalline silica, somewhat angular, medium-grained, possible chert fragments.

White Mica (8%): minute crystals disseminated in matrix, secondary.

Chlorite (15%): alteration product of matrix.

Quartz (5%): filling fractures and cracks in matrix.

Albite (10%): alteration of phenocrysts.
Matrix (70%): very fine-grained, matrix completely altered.

Proto: Dacite

Plagioclase (23%): subhedral to euhedral medium-grained crystals showing Carlsbad twinning. Locally sericitized and albitized. Occurring in clusters near phenocrysts, sharp crystal shapes, probably hydrothermally formed because of association with low-grade metapelitic chlorite, grossularite (7).

Chlorite (20%): minute aggregates of greenish brown, high birefringent crystals. Occurring with stilpnomelane and epidote. Secondary and possible primary intergrowths of quartz, lacking inclusions.

White Mica (10%): masses of dark brown, high birefringent patches, secondary, filling and altering matrix associated with stilpnomelane and epidote.

Quartz (12%): medium-grained, matrix completely recrystallized or altered. Corroded cubic crystals and patches, secondary.

Protolith: Dacite

Matrix (70%): very fine-grained, matrix completely altered.

Plagioclase, dark gray to black, weathers brown, massive, porphyritic texture.

Meta-dacite: yellowish brown, very fine- to medium-grained, porphyritic texture.

Metal-oxide: Hematite (1%): patches disseminated in matrix, secondary.

Garnet (10%): subhedral to euhedral crystals showing Carlsbad twinning. Locally sericitized and albitized. Occurring in clusters near phenocrysts, sharp crystal shapes, probably hydrothermally formed because of association with low-grade metapelitic chlorite, grossularite (7).

Albite (15%): cryptocrystalline to very fine-grained, matrix completely recrystallized or altered.

Quartz (67%): medium-grained, matrix completely recrystallized or altered. Corroded cubic crystals and patches, secondary.

Matrix (35%): cryptocrystalline to very fine-grained, matrix completely recrystallized or altered.

Plagioclase (15%): possible detrital plagioclase with partial rounding of corners, highly altered to chlorite, albite, possibly quartz.
Quartz (10%): associated with alteration of matrix. Quartz reacting with albite and filling fractures.

White Mica (10%): minute aggregates, alteration product of matrix.

Hematite (8%): cubic grains and patches of hematite occurring in veins and around grains, secondary.

Epidote (58%): alteration product of matrix, gives brownish color to rock, possibly saussurite aggregates.

Albite (25%): associated with quartz in patches.

Plagioclase (15%): relict plagioclase, largely replaced by chlorite and white mica.

Chlorite (9%): forms distinct aggregates around other Mg-rich minerals or completely altering phenocrysts.

White Mica (6%): minute aggregates, altering phenocrysts of plagioclase.

Protolith: Dacite

Matrix (47%): cryptocrystalline to fine-grained. Matrix completely altered to chlorite and calcite.

Calcite (20%): alteration product of both matrix and plagioclase phenocrysts.

Albite (60%): alteration of both matrix and phenocrysts, secondary.

Quartz (20%): minor amounts in matrix associated with albite.

Pyrite (12%): fine-grained crystals, rimmed by hematite and possible white mica.

Chlorite (12%): phenocrysts being filled and alteration of matrix.

Plagioclase (24%): highly altered by calcite and albite.

#12-18-3B). Meta-dacite; bluish-gray, oxidized red, cryptocrystalline to medium-grained, porphyritic texture, hydrothermally altered.
Quartz (5%): may either be secondary or primary quartz

Protolith: Dacite

#3-18-3). Meta-dacite; greenish-gray, very fine-grained to coarse-grained, porphyritic texture, vesicular.

Matrix (39%): very fine-grained.

Feldspar (35%): plagioclase laths, highly sericitized and albitized.

Chlorite (20%): alteration product from relict plagioclase.

White Mica (35%): recrystallization from relict matrix.

Quartz (10%): secondary silica altered from groundmass.

Plagioclase (39%): coarse-grained, polysynthetic twinned grains showing curved twin lamellae caused by deformation. Some chloritization present.

Chlorite (6%): alteration of plagioclase, secondary.

Ilmenite (1%): irregular tabular grains.

Leucoxene (3%): alteration product from ilmenite, secondary.

Calcite (12%): large areas of calcitization which may in some places be relict plagioclase grains. Also vesicles filling with calcite.

Protolith: Dacite

Subunit b1

#2-22-1). Quartzite boulder conglomerate; light gray clasts, yellowish-orange matrix, weathers reddish-orange, clasts average cobble size, poorly sorted, intense geothermal alteration of matrix.

Matrix (16%): very fine-grained.

Quartz (30%): both recrystallization of matrix to quartz and relict detrital quartz grains incorporated in matrix.
White Mica (50%): minute aggregates, secondary.
Calcite (8%): patches occurring in matrix, secondary.
Hematite (12%): occurring in veins within the matrix and around the clasts.

Metaquartzite Clasts (84%): quartzite composition with convex-concave or lobate contacts between quartz grains, poorly-sorted, well-rounded clasts.

#3-22-1).
and
#3-22-4). Quartzite boulder conglomerate: light gray, oxidized to red, cobble size clasts, poorly sorted, well-rounded.

Matrix (12%): fine-grained.

White Mica (87%): occurs around quartzite clasts and relict detrital quartz grains, secondary alteration. May originally have been a muddy matrix between clasts.
Quartz (8%): relict detrital grains, medium-grained, poorly-sorted.
Hematite (5%): disseminated throughout matrix, secondary.

Metaquartzite Clasts (88%): quartz grains look like they have been spread apart. May be due to emplacement of matrix. Lobate grain sutures, associated with relict detrital grains, no overgrowths seen, straight extinction.

Subunit b2

#3-18-2). Andesite boulder conglomerate: gray, clast supported, weathers brown to red, low sphericity, well-rounded, poorly-sorted.
Andesite Clasts (100%): boulder size clasts, low sphericity.

Matrix (45%): fine-grained, highly altered.

Feldspar (55%): plagioclase laths, locally sericitized.

Quartz (45%): recrystallized from matrix.

Biotite (4%): anhedral grains, pleochroic brown, scattered patches, secondary.

Chlorite (3%): anhedral grains, alteration product from plagioclase, secondary.

Calcite (5%): associated with plagioclase phenocrysts by replacement.

Plagioclase (35%): relict euhedral crystals, polysynthetic twinning present, andesine-oligoclase composition, calcitization and chloritization present.

Iron Oxides (4%): ilmenite (?), irregular tabular grains, relict.

Leucoxene (2%): alteration product from ilmenite, secondary.
Unit C

#1-17-1). **Meta-volcanic**: light green, weathers dark green to brown, slaty cleavage present in outcrop, cryptocrystalline to medium-grained, porphyritic texture.

Matrix (40%): cryptocrystalline to very fine-grained.

Quartz (10%): secondary intergrowths.

White Mica (90%): minute aggregates, secondary.

Plagioclase (10%): highly altered and corroded to albite and chlorite.

Quartz (20%): metamorphically formed quartz from alteration of plagioclase and ground mass, medium-grained, anhedral grains.

Epidote (5%): occurs in patches or veins around relict plagioclase, secondary.

Chlorite (15%): patches associated with epidote formation, secondary.

Iron Oxides (1%): ilmenite (?), cubic crystals, relict.

Pyrite (5%): cubic crystals disseminated in groundmass, hydrothermally formed.

Protolith: **Dacite (?) Tuff**

#1-17-2). **Meta-dacite (?)**: light gray to silver, porphyritic texture, flow banding present, alignment of plagioclase phenocrysts and micas.

Matrix (73%): cryptocrystalline to very fine-grained.

Feldspar (40%): plagioclase and sanidine (?) laths present, highly altered.

White Mica (60%): minute aggregates, optical continuity present, secondary.

Plagioclase (11%): relict plagioclase in clusters, highly corroded with zoned albite crystals.
Quartz (9%): fine-grained, euhedral, may be recrystallized from matrix and not part of original composition.

Garnet (1%): dodecahedral shape, moderately high relief. Grossularite (?).

Calcite (1%): patches, secondary.

White Mica (6%): alteration product of feldspars other than groundmass.

Iron Oxides (1%): ilmenite (?), anhedral grain shapes.

Hematite (tr.): surrounding ilmenite grains.

Leucoxene (1%): alteration product of ilmenite.

**Protolith:** Dacite (?) Tuff

---

Foliated, quartzite pebbly mudstone; gray, matrix supported, extremely poorly-sorted, foliation present in matrix, possible debri flow.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>(78%): fine-grained.</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Mica</td>
<td>(63%): fine-grained micaceous aggregates showing preferred orientation. Recrystallized from muddy matrix, metamorphic.</td>
</tr>
<tr>
<td>Organics</td>
<td>(6%): disseminated in matrix.</td>
</tr>
<tr>
<td>Quartz</td>
<td>(31%): recrystallized from silica-rich matrix.</td>
</tr>
</tbody>
</table>

Quartzite Clasts (5%): clasts average pebble size, poorly-sorted, moderately well-rounded, some rotation of clasts in matrix.

Quartz (3%): medium grain size, subrounded, somewhat fractured.

Chlorite (1%): alteration product in matrix of relict detrital grain.

Iron Oxides (4%): ilmenite (?), cubic crystals, detrital grains.

Leucoxene (5%): alteration product of ilmenite.

Epidote (4%): patches of nondescript cryptocrystalline saussurite patches.

**Protolith:** Quartzite Pebbly Mudstone
and 

Foliated, quartzite pebbly mudstone; gray to silver, matrix supported, extremely poorly sorted, foliation present in matrix, possible debris flow.

Matrix  (62%): fine-grained.

White Mica  (55%): fine-grained micaceous aggregates showing preferred orientation. Recrystallized from an originally clay rich muddy matrix.

Organics  (8%): disseminated in matrix.

Quartz  (34%): recrystallized from silica component of matrix.

Chlorite  (3%): patches occurring in matrix.

Quartzite Clasts  (20%): pebble size, poorly-sorted, moderately well-rounded, elongation present parallel to the bedding which may indicate stretching or may have originated in an elongated shape.

Quartz  (15%): medium-grained, poorly-sorted, sub-rounded, relict detrital grains.

Zircon  (tr.): relict detrital grains.

Sphene  (tr.): relict detrital grains.

Iron Oxides  (1%): ilmenite (?), relict detrital grains.

Leucoxene  (2%): alteration product of ilmenite.

Protolith: Quartzite Pebby Mudstone

Meta-rhyolite; grayish-white, weathers reddish-gray, relict flow banding present, foliated, porphyritic.

Matrix  (77%): very fine-grained.

Quartz  (50%): very fine-grained, partially recrystallized from pre-existing matrix and medium-grained vein recrystallization.

White Mica  (50%): occurs in either distinct aggregate clusters or disseminated throughout groundmass.
Quartz (9%): embayed β-quartz, medium-grained, somewhat fractured and clear.
Apatite (2%): minute aggregates occurring in both groundmass and as inclusions.
Epidote (6%): occurring in hexagonal aggregate clusters.
Hematite (2%): patches disseminated in matrix, secondary.
Iron Oxides (5%): relict cubic crystals, fine-grained.

Protolith: Rhyolite Tuff
Unit D

#1/18/5). Mica-quartz phyllite; alternating layers of gray and black corresponding to quartz-rich and mica-rich layers, slaty cleavage present, very thinly-bedded, fine laminations present.

Quartz-rich Layer (100%): silt to very fine-grained sand size.

Quartz (94%): silt size quartz grains predominate with minor amounts of very fine-grained detrital sand grains. Recrystallization occurred to medium sand size in irregular veins.

Hematite (2%): veins parallel to bedding secondary.

Iron Oxides (2%): detrital grains of ilmenite or magnetite, fine-grained.

White Mica (2%): layers of cryptocrystalline micas.

Protolith: Clayey Siltstone

#1-21-1) Carbon-rich metasiltstone; black, carbonaceous lamination, argillaceous size quartz grains, partial recrystallization of quartz.

Quartz (65%): silt size quartz grains showing straight contacts, partial recrystallization of quartz grains in irregular veins.

Carbonaceous Material (35%): very finely laminated, only occurs in non-recrystallized areas.

Hematite (tr.): disseminated in non-recrystallized areas, secondary.

Protolith: Organic Rich Siltstone

#1-21-2). Mica-quartz phyllite; silt-sized grains, well developed foliation present, partial recrystallization of quartz.
Quartz (56%): silt sized detrital grains with partial recrystallization occurring cross-cutting lamination.

White Mica (36%): minute aggregates occurring in distinct layers, crystals show optical continuity.

Biotite (2%): associated with patches of hematite

Hematite (3%): patches and veins subparallel to lamination, secondary.

Carbonaceous Material (3%): disseminated throughout non-recrystallized areas.

Protolith: Clayey Siltstone

#1-21-3). **Two-mica phyllite:** light brown, well developed foliation, silt size grains.

Quartz (48%): argillaceous size quartz, well-sorted, subangular.

Muscovite (26%): minute tabular euhedral crystals, well developed parallelism.

Biotite (23%): minute tabular crystals, foliated, pleochroic brown.

Iron Oxides (3%): silt size heavy mineral, presence indicates clastic unit.

Protolith: Silty Claystone

#1-20-9 **Meta-limestone:** gray, weathers dark grayish-brown, very thinly-bedded, minor mosaic texture.

Calcite (89%): very finely crystalline calcite, minor mosaic crystals.

Quartz (3%): silt size grains in distinct layers, subangular, moderately-sorted.

Muscovite (3%): tabular crystals parallel to layering showing bent cleavage from distortion.

Hematite (2%): disseminated in layers and patches, secondary.
Carbonaceous Material (3%) : disseminated in layers.

Protolith: Crystalline Limestone

Meta-limestone; finely laminated gray and black layers corresponding to calcite and organic rich layers, well developed microfold, finely crystalline.

Calcite (94%) : finely crystalline calcite, minor mosaic crystals.

Carbonaceous Material (6%) : disseminated in distinct layers.

White Mica (tr.): minute aggregates, secondary.

Protolith: Organic-bearing, Crystalline Limestone
Unit E

#1-18-2) Epidote, chlorite phyllite; green, weathers brownish-green, well developed foliation, fissile with slaty cleavage, cryptocrystalline to fine-grained.

Chlorite (45%): disseminated throughout relict groundmass and relict phenocrysts. Nondescript aggregates clustered together showing parallelism.

Epidote (25%): cryptocrystalline patches altered from groundmass. High relief showing slight green pleochroism. Slight optical continuity in layers.

Albite (16%): anhedral grains in close association with chlorite and muscovite. Probably a reaction product from phenocrysts of plagioclase reacting to albite and chlorite.

Muscovite (12%): distributed in relict phenocrysts formed by metamorphic reaction from feldspar.

Hematite (tr.): patchy, secondary.

Iron-Titanium Oxides (1%): ilmenite (?), anhedral grains, relict very fine-grained.

Leucoxene (1%): alteration product of ilmenite.

Protolith: Volcanic (Basalt?) Tuff

#Mb-12) Albite, chlorite phyllite; bright green, well-developed augen-shaped fabric, completely mylonitized, all grains being completely strung out due to intense shear couple.

Chlorite (32%): infills between other grains, has a stringer appearance, deformed around more competent grains.

Quartz (10%): finely disseminated and intermixed with chlorite and calcite.

Calcite (20%): highly sheared calcite grains showing bent twin lamella due to intense deformation and mylonitization.

Albite (28%): occurs in augen-shaped grains from completely altered and recrystallized relict plagioclase phenocrysts.
Plagioclase (10%): fine-grained phenocrysts completely altered to albite and calcitized, chlorite tails present. Some grains being rotated in augen-shaped fabric.

Protolith: Basic Volcanic (Basalt?)
Unit F

#1-18-1). Mica-quartz phyllite; gray and black layers corresponding to quartz-rich and mica-rich layers, weathers brownish-gray, well developed foliation, slaty cleavage, very thinly-bedded, graded bedding seen in mica-rich layers.

Quartz-rich Layer (65%): silt size grains.

Quartz (88%): silt size grains with mainly straight contacts. Minor amounts of recrystallization occurring in irregular veins.

White Mica (3%): minute aggregates showing parallelism distributed in quartz-rich layers.

Hematite (3%): layers, veins and patches, secondary.

Chlorite (4%): minute aggregates, pleochroic green, secondary.

Carbonaceous Material (2%): distributed in layers parallel to bedding.

Zircon (tr.): relict detrital grains, very fine-grained, presence indicates a clastic unit.

Mica-rich Layers (35%) silt and clay size grains.

Biotite (31%): minute aggregates, pleochroic brown, strong foliation, alteration product of clay-rich layer.

White Mica (3%): minute aggregates, secondary.

Hematite (8%): layers and patches distributed in mica-rich layer, secondary.

Quartz (38%): silt size grains.

Carbonaceous Material (12%): distributed in mica-rich layer.

Chlorite (8%): parallel to lamination in discrete layers.

Protolith: Clayey Siltstone
Mica-quartz phyllite; gray and black layers corresponding to quartz-rich and mica-rich layers; very fissile, weathers brownish-gray, argillaceous size grains.

Quartz-rich Layer (100%)

Quartz (94%): argillaceous size grains, very well-sorted, subangular, straight grain contacts.

Chlorite (3%): minute aggregates occurring in layers, secondary.

Hematite (1%): patches, secondary.

Iron-Titanium Oxides (1%): ilmenite (?), presence indicates clastic unit.

Leucosome (1%): alteration product of ilmenite, secondary.

Mica-rich Layer (0%): not in slide.

Protolith: Siltstone

Metalimestone; dark gray, weathers reddish-gray, massive, finely crystalline, partial mosaic texture.

Calcite (85%): calcite crystals showing effects of deformation, finely crystalline, partial mosaic crystals.

Quartz (7%): silt size grains, well-sorted, subangular, occurring in distinct layers.

Muscovite (5%): layers of mica showing distorted cleavage planes.

Hematite (3%): tabular crystals and patches occurring in layers and associated with micas.

Protolith: Crystalline Limestone

Sandy metalimestone; pink, weathers reddish-pink, massive, medium crystalline, minor mosaic texture.

Calcite (45%): medium crystalline calcite with minor mosaic crystals.
Quartz (40%): bimodal distribution in the coarse-calcarenite and very fine-calcarenite range; predominately very fine sand size that is subangular and moderately well-sorted. The coarse sand size is well-rounded and well-sorted and shows embayed edges.

Muscovite (2%): distributed throughout calcite.

Hematite (15%): patches of cryptocrystalline grains giving pink color to limestone.

Protolith: Crystalline Limestone
APPENDIX B

Fossil Locality Map
APPENDIX C

Summary of U-Pb Isotopic Data from the Mision Calamajué Area
About 50 mg of zircon was separated from about 150 Kg of metadacite from unit B by conventional heavy-mineral separation techniques (sample locality 12-18-2, Appendix A). Zircons were subdivided into two magnetic fractions using a Franz isodynamic separator. Each magnetic fraction was composed of clear zircons that were euhedral and translucent with the absence of visible cores. The fraction magnetic at a 0° tilt on the isodynamic separator was split into two bulk subfractions by a 200-mesh sieve. The non-magnetic fraction was also split into two bulk subfractions by a 200-mesh sieve.

The magnetic, greater-than 200-mesh zircon subfraction was analyzed by Bob Shuster at the University of Florida's geology department. Results of analyses are given below and are plotted on a concordia diagram. The analyzed subfraction was discordant and provided a Pb/Pb minimum age of 262 Ma. This date is consistent with the Carboniferous age indicated by conodonts that were collected both above and below the dated volcanic sequence.
<table>
<thead>
<tr>
<th>Zircon Size (mg)</th>
<th>Pb (ppm)</th>
<th>U (ppm)</th>
<th>204 Pb (ppm)</th>
<th>206 Pb (ppm)</th>
<th>207 Pb (ppm)</th>
<th>208 Pb (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>17.6</td>
<td>444</td>
<td>12.3</td>
<td>0.002160</td>
<td>0.083705</td>
<td>0.196881</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Apparent age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>206 Pb</td>
</tr>
<tr>
<td>238 U</td>
</tr>
<tr>
<td>207 Pb</td>
</tr>
<tr>
<td>235 U</td>
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<tr>
<td>207 Pb</td>
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<td>206 Pb</td>
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<td>0.024712</td>
</tr>
<tr>
<td>0.17535</td>
</tr>
<tr>
<td>0.051464</td>
</tr>
<tr>
<td>(157)</td>
</tr>
<tr>
<td>(164)</td>
</tr>
<tr>
<td>(262)</td>
</tr>
</tbody>
</table>
12-18-2/MAG AT 0 DEGREES, > 200 MESH

\[ \frac{206\text{Pb}}{238\text{U}} \\]

\[ \frac{207\text{Pb}}{235\text{U}} \]

\[ \text{Pb/Pb AGE} = 262 \text{ Ma} \]
12-18-2/MAG AT 0 DEGREES, > 200 MESH

Pb/Pb AGE = 262 Ma
ABSTRACT
ABSTRACT

Approximately 6,100 m of metamorphosed volcanic and sedimentary rocks are exposed near Mision Calamajue (latitude 29° 25' longitude 114° 15'). Lower green-schist metamorphism and shear cleavage parallel to axial plane foliation is pervasive in the area. The lowermost 1,000 m represent a coarsening-upward sequence of thin-bedded to massive silty claystone interlayered with limestone, pebble conglomerate and bedded chert and capped by a coarse-grained chert litharenite. Conodonts recovered from near the top of this underlying unit include Gnathodus bilineatus (Roundy) of Early Chesterian age. The overlying 2,300 m consist of intercalated basalt, hornblende andesite and dacite submarine flows, overlain by 400 m of dacite to rhyolite tuff, volcaniclastic sediments, pebbly mudstone, pebble conglomerate and metaquartzite boulder conglomerate. These rocks represent an island-arc system. Overlying the volcanic sequence is 2,000 m of very thinly-bedded clayey siltstone containing widely spaced intervals of limestone. Conodont fragments recovered from this overlying unit limit the upper age of the volcanic strata to Carboniferous. A Pb/Pb minimum age of 262 Ma was provided by the analysis of
U/Pb from one discordant zircon subfraction. This is consistent with the Carboniferous age provided by the conodonts. A highly sheared, 400 m thick basic volcanic or hypabyssal unit interfingers with this 2,000 m thick thin-bedded clayey siltstone and represents a mylonitized zone.

The study area of Mision Calamajué may be a southern extension of the Carboniferous inner-arc basin between the Antler Orogenic Highland and the Klamath-Northern Sierra Nevada island-arc. Palinspastic reconstruction along the Mojave-Sonora Megashear(s) may juxtapose the Mision Calamajué area with other island-arc sequences in the western United States.
GENERALIZED COLUMNAR SECTION OF THE PRE-BATHOLITHIC ROCKS OF MISION CALAMAJUE

**LITHOLOGY**

**DESCRIPTION**

Very thin-bedded mica-quartz phyllite showing pervasive shear cleavage containing widely spaced 3 to 5 m thick interbeds of metalmimestone.

Highly foliated, ductilely sheared, basic volcanic rock interfingering with the surrounding phyllites of units F and E.

Very thin-bedded mica-quartz phyllite showing pervasive shear cleavage containing widely spaced 3 to 5 m thick interbeds of metalmimestone.

Lithologically variable volcanogenic unit containing intermediate to siliceous volcanic tuffs, volcaniclastic sediments, sandstone and pebble conglomerate.

Vesicular volcanic sequence of intercalated green, green-brown, and brown hornblende-andesite, and gray dacite subaqueous base flows containing basalt lenses of thinly-bedded chert.

Subunit b1: Interbeds of clast supported, bright orange volcaniclastic-boulder conglomerate.

Subunit b2: Lensy clast supported andesite-boulder conglomerate.

Coarse-grained upward-beded sequence characterized by thin-bedded quartz-mica phyllite with 5 to 20 m thick interbeds of basalt banded chert, capped by 20 to 30 m thick beds of clast litharenite intercalated with 3 to 5 m thick intervals of pebble conglomerate and metalmilestone.

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**ERA PERIOD**

**UNIT**

**PALEOZOIC**

**CARBONIFEROUS**

**C**

**D**

**E**

**F**

**LITHOLOGY**

**INTERSTICE TO BASIC SHEARED VOLCANICS**

**SILICEOUS VOLCANIC TUFFS, VOLCANICLASTICS AND ABRASIVELY MUDTONES**

**METABASALT, META-ANDESITE AND METADACITE FLOWS**

**METALITHARENITE WITH METALLIMESTONE INTERBEDS**

**PHYLLITE WITH PITHYLITE WITH METALIMESTONE INTERBEDS**