GEOLGY OF THE RANCHO EL ROSARITO AREA: EVIDENCE FOR LATEST ALBIAN, EAST OVER WEST, DUCTILE THRUSTING IN THE PENINSULAR RANGES

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
Christopher Warren Goetz
Spring 1989
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In Back Pocket
CHAPTER I

INTRODUCTION

Geologic Overview

Peninsular California consists of Baja California (Mexico) and that portion of southern California (U.S.A.) that is south of the Transverse Ranges and west of the San Andreas fault system. Its most prominent feature is the northwest trending Peninsular Ranges batholith which extends from Riverside, California, south to the 28th parallel, and is believed to continue in the subsurface to the tip of the Baja Peninsula (Gastil and others, 1975; Frizzel, 1984; Todd and others, 1988). The batholith is a continuous belt of gabbroic through granitic, Cretaceous plutonic rocks that have intruded late Paleozoic and Mesozoic, metamorphic host rocks (Gastil and others, 1975). The metamorphic host rocks underwent regional dynamothermal metamorphism concurrent with the intrusion of the batholith (Gastil and others, 1975; Gastil, 1975; Todd and others, 1988). Grade of metamorphism generally increases towards the east (Gastil, 1975), ranging from greenschist to upper
amphibolite facies (Todd and others, 1988).

Gastil (1986) subdivided the metamorphic host rocks of northern Peninsular California into five lithostratigraphic terranes (Figure 1). The continental borderland terrane, and the Jurassic-Cretaceous arc terrane, are characterized by Mesozoic, volcanic and oceanic rocks which may be allochthonous to cratonal North America (Gastil and others, 1978; Coney and others, 1980, Kimbrough and others, 1987). Inboard of these western volcanogenic terranes, the Peninsular, Ballenas, and the San Felipe terranes are dominated by autochthonous, cratonally derived, Paleozoic and Mesozoic epiclastic rocks (Gastil and others, 1978; Gastil and Miller, 1983; Gastil, 1986). This study focuses on the boundary between the Jurassic-Cretaceous arc and the Peninsular terranes which is hereafter referred to as the "prebatholithic boundary" or simply "the boundary."

The Jurassic-Cretaceous arc terrane is a nearly continuous belt of volcanic and volcanioclastic rocks, of predominantly andesitic to rhyolitic composition that occurs along the western side of the Peninsular Ranges (Gastil, 1986). It extends from the Santa Anna Mountains of southern California to the southern border of Baja California Norte, and includes the Late Jurassic, Santiago Peak Volcanics (Larsen, 1948; Fife and others,
Figure 1. Prebatholithic terranes of Peninsular California (from Gastil, 1986).
north of the Agua Blanca fault and the Albian-Aptian Alisitos Formation (Santillan and Barrera, 1930; Allison, 1955, 1964, 1974; Silver and others, 1963; Reed, 1967; Beggs, 1984) to the south of the Agua Blanca fault. Collectively these volcanogenic rocks are considered the remnants of an island arc which was active during latest Jurassic through Cretaceous time (Gastil and others 1975; Silver and others, 1979).

Immediately east of the Jurassic-Cretaceous arc terrane, are the flysch-type, metasedimentary rocks of the Peninsular terrane (Gastil, 1986). In southern California three units of the Peninsular terrane have been tentatively dated from scarce fossil evidence. They are: the Triassic and Jurassic Bedford Canyon Formation (Criscione and others, 1978) of the Santa Ana Mountains, the Upper Triassic (?) French Valley Formation (Schwartz, 1969; Gastil and others, 1975) of the Hemet area, and the Triassic (?) Julian Schist (Hudson, 1922; Germinario, 1982) of San Diego County. In Baja California, along the 30th parallel, are lithologically similar, fossiliferous rocks of Lower Permian (Delattre, 1984), Upper Permian (?) to Lower Triassic (Buch, 1984), and middle Cretaceous age (Phillips, 1984a, 1984b). Mississippian conodonts have been reported from clastic and carbonate rocks.
further to the south (29° 25' N. Latitude) in Calamujame Canyon (Hoobs, 1985). The occurrence of quartz conglomerates (Phillips, 1984a, 1984b) and Precambrian zircons (Bushee and others, 1963; Gastil and others, 1988) indicates a cratonal provenance for the rocks of the Peninsular terrane.

Collectively, the lithologic, paleontologic, and zircon evidence suggests that the metasedimentary rocks of the Peninsular terrane were part of a continent-fringing clastic apron that probably was draped off the western edge of North America from late Paleozoic (?) through Early Cretaceous time (Gastil and Miller, 1983; Gastil and Miller 1984; Gastil, 1986). They are generally interpreted to represent proximal to distal turbidites that were deposited in a deep marine basin (Gastil, 1986). The tectonic setting of this basin, whether forearc, backarc or trench is not known.

The nature of the boundary between the Jurassic-Cretaceous arc terrane and the Peninsular terrane is a controversial subject. Larsen (1948) indicated that in the Santa Anna Mountains, the Santiago Peak Volcanics depositionally overlie the Bedford Canyon Formation. However, Gastil and others (1981) point out that more recent work in that area has not delineated any definitive contacts. Gastil (1986, p. 280) reports that,
"despite considerable search, no depositional contacts have been found between the arc volcanic rocks and the adjacent flysch belt to the east." Therefore, the prebatholithic boundary could be tectonic in origin and may represent a major structural discontinuity within the Peninsular Ranges.

Gastil and others (1978, 1981) proposed that the prebatholithic boundary represents a "suture zone" that formed when the Jurassic-Cretaceous arc terrane collided with and was accreted to western North America in late Mesozoic time. In support of this model, Todd and Shaw (1985), Todd and others (1988), and Griffith and Goetz (1987) suggested that the northwest trending regional fabric of the Peninsular Ranges is a consequence of the proposed arc-continent collisional event. However, the collisional event and the existence of the suture have not been widely accepted. Furthermore, the mechanisms of regional deformation in batholiths have been the subject of much recent controversy. Regional tectonite fabrics have been interpreted traditionally as evidence for crustal-scale strain related to externally imposed tectonic events (e.g., arc-continent collision). However, Gastil (1979) and Tobisch and others (1986) point out that tectonite fabrics in batholithic regions may instead be related to the forcible emplacement of
plutons. In such a scenario, the tectonite fabric is considered the consequence of internally imposed forces related to the dynamic evolution of the batholith, rather than from an externally imposed tectonic event. Considering the structure of the Peninsular Ranges batholith, two fundamentally important questions are: (1) Does the prebatholithic boundary represent a suture zone that formed from an arc-continent accretionary event? and (2) Is the regional tectonite fabric the consequence of internally or externally imposed deformation?

**Purpose**

The purpose of this investigation was to study the boundary between the Jurassic-Cretaceous arc and Peninsular terranes as it is exposed in the vicinity of Rancho El Rosarito, Baja California, Mexico (30° 30' N. latitude, Figure 2). The primary objectives were to constrain the kinematics, timing, and cause of deformation along the prebatholithic boundary. This thesis is the first detailed description of the lithologic, structural, and metamorphic characteristics of the batholithic and prebatholithic rocks in the Rancho El Rosarito area. Data from this study were compared and evaluated with other related studies in an attempt to understand the tectonic significance of the
Figure 2. Location of the study area (Rancho El Rosarito) along the prebatholithic boundary.
prebatholithic boundary and its importance in the late Mesozoic tectonic evolution of the Peninsular Ranges batholith.

**Previous Work**

Comprehensive studies on the geology of Baja California have been published by Gastil and others (1975) and Frizzel (1984). Important works that focus on the nature of the prebatholithic boundary include; Gastil and others (1978, 1981), Todd and Shaw (1985), Todd and others (1988), and Griffith (1987). Detailed descriptions of prebatholithic lithologies that are correlative to those near Rancho El Rosarito can be found in Reed (1967) and Phillips (1984). Reconnaissance maps that encompass the Rancho El Rosarito area have been published by The Consejo de Recursos Naturales no Removables (1965) and Gastil and others (1975).

Gastil and Miller (1983) were the first to specifically discuss the geology of the Rancho El Rosarito area. They wrote the following account:

It contains rocks of two very different terranes separated by a major northwest-trending fault zone. To the southwest of this fault the volcanic-volcaniclastic Alisitos Formation occurs in the form of open folds; to the northeast the rocks are predominantly non-volcanic clastic layers interbedded with a few pyroclastic beds. These rocks are intensely folded with pronounced stretching in the down-dip direction of fold lineation. The age of the northeastern rocks is unknown, but we suspect that they are correlative with the
Gastil and Miller (1984) added that the northeastern rocks are a predominantly flysch sequence which contains minor intervals of rhyolitic to andesitic volcanic rock. Gastil (1986) indicates that the thick section of flysch near Rancho El Rosarito is part of the Peninsular terrane.

**Methodology**

A 45 square kilometer area near Rancho El Rosarito, along an 8 kilometer stretch of the prebatholith boundary was geologically mapped on a 1:12,500 scale topographic base map (Plate 1). The base map was enlarged from portions of 1:50,000, Department of Estudios Del Territorio Nacional topographic maps H11B76, H11B75, H11B66 and H11B65. Field work for this study consisted of 29 days between March of 1986 and March of 1988. During geologic mapping, field work emphasized detailed descriptive analysis of mesoscopic structural fabric elements (Appendix B). Petrographic thin sections were examined to determine lithologies, conditions of metamorphism, and microstructural fabric (Appendix A). A deformed granitic gneiss was dated by U/Pb zircon isotopic techniques at the Baylor Brooks Institute of Isotope Geology to constrain the age of emplacement and
the timing of deformation (Appendix C).

Location, Accessibility, and Physiography

Rancho El Rosarito, (30° 30' N. latitude) is located in the southern Sierra San Pedro Martir Range, 300 kilometers southeast of San Diego, and 65 kilometers due east of the Mexican village of San Quintin (Figure 2). It can be reached by travelling east on a dirt road that intersects Mexican Highway 1, approximately 33 kilometers south of San Quintin (at Campo Costa Rico). Although a four-wheel drive vehicle is preferable, the study area can be accessed with a full size, two-wheel drive pickup truck.

The study area, which is within the Southern Highland Plateau geomorphic province of Baja California (Gastil and others, 1975), is characterized by steeply inclined slopes which are dissected by numerous arroyos. Elevation ranges from 1240 to 740 meters. It is dominantly vegetated with "catclaw" tree-shrubs, sage brush, and numerous varieties of cacti. Vegetation is relatively sparse and therefore the quality of exposure is excellent. The main drainage within the study area, El Rosarito, has running water during all seasons.
CHAPTER II

ROCK UNITS

Introduction

The Mesozoic rocks near Rancho El Rosarito have been divided into six informal map units (Plate 1). These units are: (1) western metavolcanic assemblage, (2) eastern metasedimentary sequence, (3) metagabbro, (4) Rancho El Rosarito gneiss, (5) mixed zone, and (6) tonalite. Nonconformably overlying this Mesozoic assemblage are scattered exposures of Miocene (?) fluvial conglomerate and the recent alluvium of the Rosarito drainage. The general lithologic characteristics of these units are described in this chapter. Detailed petrographic descriptions of representative rocks from the Mesozoic units are presented in Appendix A.

Western Metavolcanic Assemblage (Kmv)

Metavolcanic rocks near Rancho El Rosarito crop out within the western portion of the field area and are referred to collectively as the "western metavolcanic assemblage" (WMA). Although the dominantly massive character of this assemblage prevents a simple
stratigraphic subdivision, it is generally comprised of volcanic flows, lapilli tuffs, and ash fall tuffs. These rocks have been regionally metamorphosed but are not foliated and have retained most of their original igneous characteristics.

Perilait-Montoya (1968) identified a Cretaceous bivalve (Lima sp.) from the metavolcanic rocks near Rancho El Rosarito, within Canada El Gringo. This genus also has been collected from the Alisitos Formation at its type locality near Punta China (Allison, 1964) and from Alisitos type rocks that crop out 30 kilometers to the south, near El Rosario (Reed, 1967). The WMA is therefore considered to be correlative with the Lower Cretaceous Alisitos Formation.

Volcanic Flows

Volcanic flows of rhyolitic to dacitic composition are the predominate rock type of the WMA. They are light to medium gray on fresh surfaces, weather to shades of reddish brown, are well indurated, and commonly porphyritic. In thin section, plagioclase and potassium feldspars commonly occur as euhedral phenocrysts within a felty groundmass of quartz, feldspar, epidote, chlorite, altered glass, and opaques. Most commonly the plagioclase phenocrysts are randomly oriented, but locally they define a weakly to moderately well developed trachytic
Basalt flows are a rare constituent of the WMA. Where present they generally occur as laterally discontinuous tabular bodies that are characteristically massive, well indurated, and porphyritic. They are dark gray to black on fresh surfaces, but upon weathering are sometimes indistinguishable from weathered dacites and rhyolites. Thin-section study reveals that randomly oriented plagioclase and augite phenocrysts occur within a chlorite, epidote-rich matrix. A conspicuous body of basalt that crops out adjacent to the road, approximately 1.5 kilometers north west of Rancho El Rosarito, exhibits structures that resemble pillows (Figure 3), suggesting emplacement as a submarine lava.

**Lapilli Tuffs**

Lapilli tuffs (Figure 4) are a minor constituent of the WMA. They are generally clast supported, poorly sorted, massive, and well indurated. Lapilli range to a maximum size of 42 mm. Thin-section study reveals a heterogeneous clast population that is dominated by angular to sub-angular, plagioclase-rich, volcanic fragments. The interstitial matrix is dominated by chlorite, epidote and feldspar microphenocrysts.
Figure 3. Pillow (?) basalt from the western metavolcanic assemblage exposed near the prebatholithic boundary.
Figure 4. Polished slab of lapilli tuff from the western metavolcanic assemblage. Clasts are plagioclase-rich volcanic fragments. Matrix is dominated by chlorite, epidote and plagioclase.
**Ash Fall Tuffs**

Vitric and lithic ash-fall tuffs are a widespread constituent of the WMA. Although locally very well bedded (Figure 5), they are more commonly massive, generally occurring in blocky outcrops (Figure 6). They are characteristically well indurated, light gray to cream colored on fresh surfaces, and yellow brown to tan on weathered surfaces. They are cryptocrystalline, apparently composed almost entirely of extremely fine lithic and vitric dust.

**Eastern Metasedimentary Sequence (Kms)**

Metasedimentary rocks near Rancho El Rosarito crop out as a well bedded, northwest-trending, east-dipping homoclinal section (Figure 7) that is referred to herein as the "eastern metasedimentary sequence" (EMS). Cropping out within an approximately three-kilometer-wide zone, it has an exposed thickness of nearly two kilometers. It is dominated by an alternating sequence of pelites, quartzo-feldspathic sandstones, cherts and tuffs that have been variably metamorphosed to slate, phyllite, schist, gneiss, quartzite, and granofels. Marbles are uncommon within this sequence. Metamorphism and deformation have destroyed most of the sedimentary textural features of these rocks. The age of the EMS is
Figure 5. Well bedded ash-fall tuff from the western metavolcanic assemblage. Rock hammer near center of photo is 30 centimeters long.
Figure 6. Ash-fall tuff from the western metavolcanic assemblage. Note the massive outcrop habit which is characteristic of the rocks west of the prebatholithic boundary.
Figure 7. View towards the south (along strike) within the eastern metasedimentary sequence. Note the well bedded nature of this east dipping unit.
unknown; however, Gastil and Miller (1984) have suggested that these rocks may be correlative to lithologically similar, Cretaceous rocks near La Olvidada (30° N. Latitude).

**Slates and Phyllites**

Slates and phyllites are abundant, comprising an estimated 50 percent of the EMS. They are predominantly limited to within a kilometer of the prebatholithic boundary. They are highly variegated, occurring in various shades of yellow to reddish brown, gray, and green. They are thinly bedded, commonly laminated, moderately well indurated and weakly to strongly foliated and lineated. Although laterally continuous at outcrop scale, individual beds rarely can be traced for large distances. Dominantly composed of clay- and silt-sized particles, they locally contain relict sand-sized quartz grains. Mineralogically these rocks are dominated by very-fine-grained recrystallized quartz, plagioclase and potassium feldspar, chlorite, biotite, and sericite.

**Mica Schists**

Fine- to coarse-grained, biotite-muscovite schists comprise an estimated 30 percent of the EMS. They dominate the structurally higher, eastern portion of the sequence. They are generally dark colored, occurring in
shades of gray, brown, and black. They are characteristically thin bedded, very well indurated and are pervasively foliated and lineated. As a consequence of their greater resistance to weathering, the boundary with the underlying slate/phyllite part of the section coincides with a significant break in slope. As with the slates and phyllites, individual beds rarely can be traced for large distances, generally pinching out over distances of tens of meters. Mineralogically these rocks are dominated by quartz, potassium and plagioclase feldspar, biotite, and muscovite. In thin section it can be seen that the subparallel alignment of the [001] plane of micas define a bedding parallel foliation (Figure 8)

Paragneisses

Some of the easternmost metasedimentary rocks exhibit gneissic textures. Such rocks comprise an estimated five percent of the EMS. They are megascopically banded, comprised of alternating granoblastic (quartz and feldspar) and schistose (biotite and muscovite) layers. They are very well indurated, pervasively foliated and lineated, and commonly occur in shades of reddish gray. Mineralogically they are dominated by quartz, potassium and plagioclase feldspar, biotite and muscovite. Some of the gneisses contain garnet porphyroblasts as large as two centimeters in
Figure 8. Photomicrograph (crossed nicols) of biotite schist from the eastern metasedimentary sequence. The subparallel alignment of the [001] plane of biotite defines a well developed bedding parallel foliation.
Quartzites and Granofels

Non-schistose, metasedimentary rocks (quartzites and granofels) comprise an estimated 10 percent of the EMS. The quartzites (metacherts) are comprised almost entirely of microcrystalline granoblastic quartz with minor micas and opaques (Figure 9). They are aphanitic, commonly light to dark gray, extremely well indurated, and finely laminated. They are highly resistant to weathering, and when of sufficient thickness, form prominent outcrops that are laterally continuous for large distances. The granofels are comprised of silt-sized, granoblastic quartz and feldspar. They are commonly light colored, thinly bedded, and well indurated.

Metatuffs

Metamorphosed tuffs of intermediate to felsic composition comprise an estimated five percent of the EMS. They commonly are well foliated and often contain lapilli that are stretched in the down-dip direction. In thin section, they generally contain subhedral to anhedral plagioclase phenocrysts and quartz-rich lapilli that occur within an anastomozing foliated matrix of quartz, hornblende and biotite.
Figure 9. Photomicrograph (crossed nicols) of a quartzite from the eastern metasedimentary sequence that is comprised almost entirely of microcrystalline granoblastic quartz. Concentrations of carbon define the dark laminae.
Marbles

Marbles are extremely rare, comprising less than one percent of the EMS. They occur as scattered, laterally discontinuous outcrops. They are thinly bedded and finely laminated and occur in shades of white, gray and brown. Mineralogically they consist of fine- to medium-grained polygonal calcite with minor quartz, and feldspar.

Metagabbros (Kmg)

Metagabbros crop out along a narrow, northwest trending zone within the eastern metasedimentary sequence. They occur as northwestwardly elongate, lenticular bodies that are concordant with their metasedimentary host. They appear to be map scale, layer parallel boudins. Their outermost margins are pervasively foliated and lineated, whereas their central portions are characterized by igneous textures. Commonly about sixty meters in width, the largest metagabbro body is approximately 250 meters thick. They form prominent ridges that weather to distinctive reddish browns and thus are easily recognized from a distance. Petrographic analysis of a typical gabbro from this unit (appendix A, sample 97) produced a mode of 51% augite, 43% diopside, 24% plagioclase, and 4% sphene.
Rancho El Rosarito Gneiss (Kgn)

The northeasternmost and structurally highest unit in the field area is a pervasively foliated and lineated granitoid that is referred to as the Rancho El Rosarito gneiss (RERG). The RERG concordantly overlies the EMS and the rocks of the "mixed zone". Because of preferential erosion along foliation planes, it commonly weathers out in northwest-trending, east-dipping slabs (Figure 10). Although it includes rocks that range from mafic to felsic, it is dominated by rocks of granodioritic composition. Petrographic analysis of a typical granodiorite from the RERG (appendix A, sample 267) produced a mode of 39% quartz, 42% plagioclase, 11% potassium feldspar, 8% biotite.

Mixed Zone (Kmp)

The boundary between the RERG and the EMS is a 0.3- to 2-kilometer-wide zone that includes both metasedimentary and metaplutonic rocks. It has been mapped as a separate unit referred to as the "mixed zone". It is comprised of schists and paragneisses that have been invaded by felsic to mafic intrusives. The intrusives occur as northwest trending, lenticular bodies that are generally concordant with their metasedimentary host. Commonly less than a couple of meters thick, these
Figure 10. View towards the north within the Rancho El Rosarito gneiss. Note the tabular weathering habit of this unit which is a consequence of preferential erosion along a penetrative northwest-trending east-dipping foliation.
sill-like intrusives rapidly pinch out along strike. They are thicker and more abundant towards the RERG from which they have apparently emanated. The upper, eastern boundary with the RERG is a sharp contact that is marked by the easternmost occurrence of metasedimentary rock. A gradational western boundary with the underlying metasedimentary sequence was arbitrarily chosen where intrusives comprise less than ten percent of the rock.

**Tonalite (Kt)**

Intrusions of tonalitic composition occur in the northwest portion of the field area near the Santa Eulalia drainage. They appear to be part of an outer, more silicic facies of a largely gabbroic pluton that crops out immediately to the north of the field area. Contrasting sharply with the granitoids of the RERG, these intrusives are not lineated and only moderately foliated. The trend of the foliation varies from N36E to N50W and the dip ranges from 60N to vertical. Some of the contacts with the host metasedimentary rocks are clearly discordant. Petrographic analysis of a typical tonalite from this unit (appendix A, sample 218) produced a mode of 54% plagioclase, 34% quartz 5% potassium feldspar, 6% biotite and trace hornblende.
**Tertiary Conglomerate (Tfc)**

Unconsolidated conglomerate nonconformably overlies the WMA in the southernmost corner of the field area (near Canada El Gringo) and also the RERG in the east central portion of the field area. It is composed mostly of poorly sorted, subangular to subrounded, metavolcanic and granitic pebbles and cobbles. This unit is of undetermined age, but to the south of the field area is overlain by Upper Miocene volcanic rocks (Gastil and others, 1975). Gastil and others (1975) assigned a Miocene (?) age to these immature fluvial deposits.

**Quaternary Alluvium (Qal)**

A substantial accumulation of Quaternary alluvium occurs within the Rosarito drainage. These sediments are comprised of poorly sorted, sub-angular sand and gravel derived primarily from granitic rocks.
CHAPTER III

METAMORPHISM

Introduction

The prebatholithic rocks of the Peninsular Ranges have undergone regional dynamothermal metamorphism concurrent with intrusion of the batholith (Gastil and others, 1975; Gastil, 1978; Todd and others, 1988). Near Rancho El Rosarito the rocks exhibit mineral assemblages and metamorphic textures that indicate a west to east increase in the degree of metamorphism. East of the boundary, this is readily apparent on a macroscopic scale, as slates, phyllites, schists, and gneisses are progressively encountered towards the east. Petrographic study indicates that this eastward increase in metamorphic grade ranges from greenschist (low grade) to amphibolite facies (medium grade).

Diagnostic Mineral Assemblages

Eskola (1915) introduced the concept of "metamorphic facies" to designate a group of rocks that were characterized by a definite set of minerals formed under particular metamorphic conditions. Eskola's metamorphic
Figure 11. Metamorphic pressure-temperature diagrams outlining various (a) facies (from Eskola, 1939) and (b) grades (from Winkler, 1979).
The facies/pressure-temperature diagram (Figure 11a) has since become the foundation for modern classifications of metamorphic rocks. Winkler (1979) proposed that the nomenclature of metamorphic facies be dropped in favor of metamorphic grade. He favors the terms very low, low, medium, and high grade metamorphism over Eskola's zeolite, greenschist, amphibolite, and granulite facies (Figure 11b).

According to Turner (1981), the lower limit of Eskola's greenschist facies is marked by the elimination of pumpellyite in favor of epidote (where proceeded by pumpellyite facies). He considers albite plus epidote to be the diagnostic pair common to mineral assemblages derived from shales, graywackes, and basic volcanics. In pelitic rocks, other characteristic greenschist facies minerals include phengitic muscovite, chlorite, sphene, chloritoid, and stilpnomelane. Basic assemblages are characterized by chlorite, actinolite, talc, and tremolite. Winkler (1979) and Turner (1981) indicate that biotite occurs at higher grades within the greenschist facies. Notable absentees from lower grade rocks are zeolites, prehnite, pumpellyite, and lawsonite.

Albite and epidote, as well as chlorite and muscovite, are the common metamorphic minerals of the western metavolcanic assemblage. Sub-greenschist facies
minerals such as zeolites, prehnite, pumpellyite, and lawsonite, were not observed. From the above criteria, the western metavolcanic assemblage is considered to have undergone at least greenschist facies metamorphism. This conclusion is in agreement with other studies which indicate that volcanic rocks in the Alisitos Formation have generally been metamorphosed to greenschist facies (Reed, 1967; Gastil and others, 1975; Beggs, 1984).

The albite-epidote-chlorite-muscovite assemblage continues across the prebatholithic boundary into the eastern metasedimentary sequence. Further to the east, within the metasedimentary unit, a "biotite in" isograd is roughly delineated (Plate 1), indicating the occurrence of higher greenschist facies conditions. The first appearance of metamorphic garnets occurs east of this isograd. If these are almandine-rich garnets, then they indicate the higher temperature part of low grade (greenschist facies) metamorphism, distinctly above the biotite in isograd (Winkler, 1979). Pressures and temperatures of four kilobars at 500°C and five kilobars at 600°C must be exceeded to produce an almandine-rich garnet (Winkler, 1979). Some of the structurally highest and easternmost metasedimentary rocks contain sillimanite and or staurolite (Figure 12), indicating that metamorphic grade has progressed into amphibolite facies (Turner, 1981; Winkler, 1979).
Figure 12. Photomicrograph (plain light) of amphibolite facies paragneiss from the mixed zone. Note the occurrence of staurolite (high relief, yellow mineral) and sillimanite (fibrous mineral).
"Barrovian" Metamorphic Zones

Barrow (1893, 1912) first documented the progressive nature of regional metamorphism based on mineralogic and textural changes observed in pelitic rocks of the Scottish Highlands. In passing from slates to coarse grained, sillimanite-garnet-mica schists, Barrow mapped successive zones marked by the occurrence of corresponding index minerals. Barrow's zonal sequence, in order of increasing metamorphism is: (1) chlorite, (2) biotite, (3) garnet, (4) staurolite, (5) kyanite, (6) sillimanite.

The metamorphic transformations of the rocks near Rancho El Rosarito are reminiscent of Barrow's zonal sequence. From the petrographic data (Appendix A), a chlorite, biotite, and possibly garnet, zonal sequence can be delineated. The index minerals, sillimanite and staurolite have also been identified. These data clearly indicate that an eastward "Barrovian style" progression is characteristic of the Rancho El Rosarito area.
CHAPTER IV

DESCRIPTIVE STRUCTURAL GEOLOGY

Introduction

The prebatholithic boundary is distinguished by a west to east change in host rock lithology across the Peninsular Ranges batholith. In the vicinity of Rancho El Rosarito the prebatholithic boundary is also marked by an abrupt change in structural style and magnitude of strain. Deformation of the western metavolcanic assemblage is characteristically nonpenetrative, whereas the metamorphosed sedimentary and plutonic rocks east of the boundary are intensely and multiply deformed L-S tectonites.

Structure of the Western Metavolcanic Assemblage

Except immediately adjacent to the boundary, the western volcanic assemblage is remarkably undeformed. The occurrence of randomly oriented to sub-parallel igneous textures indicate that these rocks have not undergone significant internal distortion (Figure 13). However, adjacent to the boundary (generally within 200 meters), the metavolcanic rocks exhibit a spaced to
Figure 13. Photomicrograph (crossed nicols) of volcanic flow from the western metavolcanic assemblage. Note the random orientation of the feldspar microphenocrysts which indicates that this rock has not undergone significant internal distortion.
continuous cleavage that consistently trends northwest and dips steeply towards the east. Significantly, this cleavage strikes parallel to and becomes more penetrative towards the boundary.

Because the western metavolcanics are characteristically massive, folding is not readily apparent. Minor folds were not observed. However, locally there are some well bedded units, and the overall bedding geometry does suggest the occurrence of large scale folding of the WMA. Away from the boundary, bedding generally strikes northwest and dips moderately towards the west, whereas near the boundary it consistently dips steeply towards the east. As illustrated in the authors schematic sketch (Figure 14), the bedding geometry might be the consequence of large scale drag associated with east over west thrusting along the prebatholithic boundary. However, the predominantly massive character of the volcanics, the discontinuous occurrence of well bedded units, and the absence of topping directions has prevented confirmation of this proposed structure.

Structure of the Eastern Metasedimentary and Metaplutonic Rocks

In sharp contrast to the rocks west of the boundary, the metasedimentary and metaplutonic rocks east of the
Figure 14. Field sketch of hypothesized drag structure that produced the bedding geometry within the western metavolcanic assemblage.
boundary are intensely and multiply deformed. Structural analysis of these rocks indicates that an intense episode of penetrative deformation (main phase deformation) was followed by at least three "post main phase" deformations.

"Main Phase" Structures

**Foliation and lineation.** Main phase deformation \((D_1)\) produced a penetrative, secondary foliation \((S_1)\) and lineation \((L_1)\) in most of the rocks east of the prebatholithic boundary (Figure 15). \(S_1\) characteristically strikes northwest and dips moderately to the east, whereas \(L_1\) consistently rakes steeply within the plane of foliation (Figure 16). \(S_1\) is always parallel to lithologic layering \((S_0)\), and is generally defined by the preferential alignment of phyllosilicate minerals (slaty cleavage, phyllitic structure, schistosity) or by compositional bands of different mineralogy (gneissic structure). \(L_1\) is typically an extensional, streaky mineral lineation defined by either aligned inequent minerals or mineral aggregates.

**Minor folds.** \(D_1\) also produced, minor, similar style, isoclinal folds (Figure 17). Axial surfaces of \(D_1\) folds \((S,a)\) consistently strike northwest and dip moderately to the east (Figure 18), parallel to the
Figure 15. View of the plane of foliation in a quartzite from the eastern metasedimentary sequence. Note the well developed mineral lineation that plunges steeply within the plane of foliation.
Figure 16. Contoured equal area stereonet plot of S₁ and L₁ data. This plot shows that S₁ characteristically strikes northwest and dips moderately to the east and L₁ consistently rakes steeply within the plane of foliation.
Figure 17. Similar style, isoclinal, D, fold developed in rocks of the eastern metasedimentary sequence. D, folds are axial planar to the foliation and have fold axes that are parallel to the lineation.
foliation. Fold axes \((F_1)\) consistently plunge towards the northeast (Figure 18), parallel to the extensional mineral lineation. The occurrence of isoclinal folds, parallelism of \(S_0\) with \(S_1\) and the lateral discontinuity of \(S_0\) suggests transposition of \(S_0\) during \(D_1\).

**S-C mylonitic fabric.** In the Rancho El Rosarito gneiss (RERG), \(D_1\) produced two distinct foliations (Figure, 19): \(S\) ('schistosite') and \(C\) (cisaillement) planes (Berthe and others, 1979). \(S\) planes are defined by the preferential orientation of biotite, quartz, and feldspar which are thought to grow approximately perpendicular to the short axis of the finite strain ellipsoid. Hence, \(S\) planes represent the approximate plane of finite flattening (Ramsay and Graham, 1970). In the RERG, \(S\) planes strike approximately northwest and dip 60 ± 5 degrees to the east. According to Berthe and others (1979), the \(C\) planes represent discrete shear bands that deflect \(S\) planes with a consistent sense of shear. In the RERG, \(C\) planes appear as thin layers of recrystallized, grain-size reduced, polymineralic aggregates (Figure 20) with a preferred mineral alignment (extensional mineral lineation) in the down dip direction. They consistently are spaced 10 ± 4 mm apart, strike northwest, dip 30 ± 5 degrees to the east, and deflect \(S\) planes with an east over west sense of shear.
Figure 18. Equal area stereonet plot of $D_1$ fold fabric data. This plot shows that axial surfaces $(S,a)$ trend northwest and dip moderately to the east and fold axes $(F_1)$ plunge moderately to the northeast.
Figure 19. Cut and polished slab of S-C mylonite from the Rancho El Rosarito gneiss. Note the synistral deflection of the S planes into the C planes. In outcrop C planes consistently deflect S planes with an east over west sense of shear.
Figure 20. Photomicrograph of S-C mylonite from the Rancho El Rosarito gneiss. Note the characteristic grain size reduction within the C plane.
Much of the RERG does not exhibit a composite planar, (S-C) fabric. Adjacent to its boundary with the underlying mixed zone, only one foliation is prevalent. Berthe and others (1979) indicate that when orthogneiss development intensifies (with increased strain), the angle between the S and C surfaces (initially 45°) decreases by rotation of the S surfaces into parallelism with the C surfaces until eventually the two surfaces cannot be distinguished. Parallelism of the S and C surfaces may have occurred in the portions of the RERG that experienced the greatest strain. The gneisses that contain only one foliation commonly exhibit the greatest grain size reduction and mineral elongation, characteristics that indicate higher magnitudes of strain.

Post "Main Phase" Structures

A number of structures deform and therefore post-date the penetrative D₁ fabric. Post main phase deformation produced two domainal sets of minor structures (D₂ and D₃), and a large, map scale, flexure (D₄). It is important to note that although these deformational episodes clearly post-date D₁, their sequence relative to each other is not established. For example, D₄ does not necessarily post-date D₃. It also
should not be assumed that structures of different ranking formed during separate tectonic events. For example, both $D_1$ and $D_2$ structures may have occurred during a single episode of protracted, progressive deformation.

**$D_2$ structures.** $D_2$ structures occur in several widely scattered domains that are located immediately east of the prebatholithic boundary (Plate 1, domains 1-7). They consist of open to tight, parallel to similar style, minor folds that have northwest trending, vertical to steeply dipping axial surfaces ($S_2$), and fold axes ($F_2$) that plunge predominantly to the northwest (Figure 21, Appendix B). The orientation of $S_2$ indicates southwest-northeast directed contraction. $D_2$ folds include a continuum of structures, where progressive tightening of the interlimb angle is accompanied by progressively shallower east dipping axial surfaces ($S_2$) and progressively steeper plunging axes ($F_2$). Many of the tighter $D_2$ folds are asymmetric, exhibiting westward vergence (Figure 22).

**$D_3$ Structures.** $D_3$ structures consist of minor, open to tight, parallel style folds (Figure 23) and an associated crenulation cleavage. $D_3$ folds generally trend northeasterly, have steeply west dipping axial
Figure 21. Contoured equal area stereonet plot of $D_2$ fold fabric data. This plot shows that axial surfaces ($S_2$) characteristically strike northwest and dip steeply, and fold axes ($F_2$) plunge to the northwest and to the southeast.
Figure 22. Asymmetric D₂ fold that exhibits westward vergence. West is to the left of the photo.
Figure 23. $D_3$ kink folds developed in phyllites immediately adjacent to the prebatholithic boundary.
surfaces \((S_3)\) and axes \((F_3)\) that plunge consistently towards the northeast (Figure 24). These structures primarily occur in a single domain immediately adjacent to the prebatholithic boundary (Plate 1, domain 8). They also occur as isolated structures that are generally found near the prebatholithic boundary. The orientation of \(S_3\) indicates southeast-northwest directed (boundary and bedding parallel) contraction.

**D\(_4\) Structure.** A map-scale flexure indicates the occurrence of post-tectonic deflection of the eastern domain rocks in the northernmost portion of the field area (Plate 1). Lithologic boundaries, bedding, and \(S_1\) are all deflected towards the north. The structural grain locally strikes north-south and dips moderately to the east. \(L_1\) continues to plunge steeply within the plane of foliation.
Figure 24. Equal area stereonet plot of D_3 fold fabric data. Mean S_3 strikes northeasterly and dips steeply towards the west. Fold axes (F_3) consistently plunge towards the north.
CHAPTER V

GEOCHRONOLOGY

Introduction to Uranium - Lead Dating

Uranium has two naturally occurring radioactive isotopes that have proven useful for radiometric age determinations; $^{238}\text{U}$ and $^{235}\text{U}$. $^{238}\text{U}$ and $^{235}\text{U}$ decay through a series of intermediate daughter products to $^{206}\text{Pb}$ and $^{207}\text{Pb}$, respectively (Faure, 1977). If it can be assumed that a uranium bearing mineral has remained closed to uranium gain or lead loss then a valid age can be determined from the radiogenic Pb to radioactive U ratios. The great advantage of the U-Pb decay system is that it provides two independent geochronometers, $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ and, therefore, the assumption of a closed system can be easily tested (Gebauer and Grunenfelder, 1979). When the system has remained closed, the $^{206}\text{Pb}/^{238}\text{U}$ and the $^{207}\text{Pb}/^{235}\text{U}$ ages will agree within analytical uncertainties, and it is said that the ages are internally concordant (Gebauer and Grunenfelder, 1979).
Although other uranium bearing minerals (e.g. sphene, apatite, uraninite, monazite) can be used, zircon is by far the most frequent mineral dated by the U-Pb method (Gebauer and Grunenfelder, 1979). It is widely distributed in a variety of rocks and is highly retentive with respect to uranium and lead (Faure, 1977). Zircon is preferred because it typically contains very little initial lead, and therefore has very high U-Pb ratios. This characteristic enhances its sensitivity as a geochronometer (Steiger and Wasserburg, 1969).

**U-Pb Analysis of the Rancho El Rosarito Gneiss**

U-Pb zircon isotopic data were obtained from a deformed, peraluminous granite of the RERG. Zircons were extracted from a 150 kg sample by conventional crushing, heavy liquid, and magnetic separation methods. The recovered zircons were euhedral, doubly terminated and lacked visible cores. The U-Pb isotopic analyses were performed by Melissa Wardlaw at the Baylor Brooks Institute of Isotope Geology, San Diego State University. Data and analytical procedures are presented in Appendix C. These data define a concordant U-Pb emplacement age of 108 ± 1 ma.
Significance of Data

The primary objective of determining the U-Pb age for the RERG was to constrain the timing of penetrative D₁ deformation. The U-Pb zircon age for the RERG indicates that D₁ must have occurred later than 108 m.y. ago. Through reconnaissance mapping and aerial photography, the D₁ fabric is seen to be regionally developed, extending for many (hundreds) kilometers to the north and south of the field area (Griffith and Goetz, 1987). Thirty kilometers north of Rancho El Rosarito, the D₁ fabric appears to be crosscut by the concentrically foliated (Eastman, 1986; McKormick, 1986) Sierra San Pedro Martir pluton (Figure 25). If this observation is correct, then an approximate U-Pb emplacement age of 95 Ma. for the Sierra San Pedro Martir pluton (McCormick, 1986) places an upper constraint on D₁. It appears that D₁ deformation near Rancho El Rosarito is constrained between 108 and 95 Ma. (Albian). This interpretation is in agreement with Silver and others (1979) who suggest that the major deformation within the batholith took place not much later than 105 m.y. ago.
Figure 25. Reconnaissance geologic map from Sierra San Pedro Martir pluton to Rancho El Rosarito area (modified from Gastil and others, 1975). Note that the regional fabric ($D_1$) appears to be crosscut by the Sierra San Pedro Martir pluton. Approximate U-Pb ages of 95 Ma. for the undeformed Sierra San Pedro Martir pluton (SSPM) and 108 Ma. for the deformed Rancho El Rosarito gneiss (RERG) suggest that $D_1$ occurred circa 100 million years ago.
CHAPTER VI

DATA INTERPRETATION

Introduction

Structural and metamorphic data presented in this thesis unequivocally indicate that in the Rancho El Rosarito area the prebatholithic boundary had a structural, fault related history. The minor structures and metamorphic gradient strongly suggest that major east over west ductile thrusting occurred along and adjacent to the boundary. U-Pb ages for the RERG and the SSPM pluton appear to constrain this deformation to the time interval between 95 and 108 Ma.

Discussion

In the Rancho El Rosarito area, the metamorphic assemblages and the change in structural style suggest that there is an eastward increase in structural level. The western metavolcanic assemblage is characterized by primary igneous textures, greenschist facies mineral assemblages and mild degrees of deformation. In sharp contrast, the rocks east of the boundary are intensely
deformed L-S tectonites of greenschist to amphibolite facies (metamorphic grade increases towards the east).

Deeper structural levels have been suggested by several workers to occur in more eastward portions of the Peninsular Ranges batholith (Gastil, 1975; Grove, 1987; Todd and others, 1988). This feature is in part the consequence of westward tilting of the batholith during the late Cretaceous and early Tertiary (Gastil and Bushee, 1961). However, in places, where the gradient is especially steep, further mechanisms seem to be required. For example, Todd and others (1988) have invoked Early Cretaceous, east over west ductile thrusting along the Cuyamaca Laguna Mountains Shear Zone (CLMSZ) to explain an apparent west to east increase in exposed structural level seen in the Peninsular Ranges of southern California. Although recent microstructural analyses of the CLMSZ by Stinson and others (1988) and Leeson and others (1989) shed doubt upon this proposal, east over west thrusting remains an attractive explanation for the eastward increase in depth that is characteristic of the Peninsular Ranges batholith.

In the Rancho El Rosarito area, east over west ductile thrusting is supported by structural data. Both D₁ and D₂ structures are compatible with west directed thrusting along and adjacent to the pre-batholithic
boundary. D₃ and D₄ structures appear to be the consequence of later, unrelated deformations. In the following paragraphs the significance of D₁ and D₂ structures are discussed relative to the proposed east over west thrust faulting and possible causes of D₃ and D₄ are briefly enumerated.

Significance of the Tectonite Fabric: Foliation (S₁) and Lineation (L₁)

Controversy has existed for years concerning the processes that are responsible for the formation of foliation and lineation (Hobbs and others, 1976). At issue is the relative importance of progressive pure shear (non-rotational deformation) versus progressive simple shear (rotational deformation). Are foliations primarily the result of preferential mineral growth perpendicular to the direction of maximum finite shortening or do they represent planes of simple shear? Do extensional lineations form from oriented mineral growth in the direction of maximum finite extension or are they the result of rotational deformation of preexisting grains? Do extensional lineations represent the direction of tectonic transport? In most tectonites these questions are not easily answered.

There are several lines of evidence that suggest that simple shear was the dominant process near Rancho El
Rosarito: (1) simple shear locally occurred along C planes within the RERG (Figure 20), (2) simple shear processes best explain the structural emplacement of the RERG over the EMS along a low angle contact, and (3) simple shear processes are required to produce asymmetric folds (e.g. west-vergent D₂ folds). If simple shear is the dominant process that produced the tectonite fabric, then the geometry of this fabric is indicative of a northwest-trending, east-dipping shear zone within which dip-slip motion was dominant.

**Significance of the Rancho El Rosarito Gneiss**

The RERG represents a previously unrecognized, Early Cretaceous ductile shear zone in the Peninsular Ranges batholith. The sense of shear determined from the S-C fabric of the RERG indicates that the eastern side was thrust over the western side. The overall geometry and fabric of the RERG is remarkably similar to that of the Eastern Peninsular Ranges Mylonite Zone (EPRMZ), a Late Cretaceous, west-directed thrust in southern California (Simpson, 1984; Sharp, 1979; Todd and others, 1988). Collectively, the RERG and the EPRMZ indicate that widespread west directed thrusting was occurring in the Peninsular Ranges during the Cretaceous.
Significance of Minor D₁ and D₂ Folds

As mentioned in Chapter 4, D₁ folds are characteristically isoclinal, have axial surfaces that are parallel to S₁ foliation, and fold axes that are parallel to the extensional mineral lineation (L₁). D₂ folds are open to tight, strike parallel to, but dip more steeply, than S₁, and have fold axes that are oblique to L₁. The style and orientation of these minor folds relative to the tectonite fabric is similar to analogous structures in shear zones worldwide (Bryant and Reed, 1969; Escher and Watterson, 1974; Bell, 1978).

Based upon observations near the Blue Ridge thrust sheet of the southern Appalachians, Bryant and Reed (1969) proposed a mechanism to explain the relationship between minor folds and tectonite fabrics near major thrust faults. They believed that the tighter folds with lineation parallel axes evolved from earlier developed, more open folds that originally had axes perpendicular to the lineation. Tightening and flattening of the folds towards the plane of foliation, and rotation of their axes toward the direction of tectonic transport (extensional lineation direction) was the result of penetrative deformation during thrusting. They suggest that individual folds may have started at different times, such that the tighter folds are older than the
open folds which formed near the end of penetrative deformation.

The similarity of style and orientation of minor folds and tectonite fabric in the Rancho El Rosarito area to that described by Bryant and Reed (1969) for the Blue Ridge thrust sheet in the southern Appalachians suggests similar origins (progressive simple shear). It is therefore suggested that the D₁ folds of Rancho El Rosarito were tightened and passively rotated into parallelism with S₁ and L₁ from more open, "D₂ style", folds during the east over west ductile thrusting (D₁) that brought mylonitic gneisses and amphibolite grade metamorphics over greenschist facies rocks. The D₂ folds represent late stage structures that formed during the waning stages of thrusting and thus had not been rotated into parallelism with S₁ and L₁.

Significance of West Verging D₂ Folds

Stille (1924, 1930) introduced the term "vergenz" (vergence) to describe the directional sense of overturning of asymmetric minor folds. Roberts (1974) succinctly defined it as; "the horizontal direction, within the plane of the fold profile in which the upper long limb has appeared to move to cause the rotation of the short limb". Stille (1924, 1930) demonstrated that fold vergence can be used to determine the sense of
transport associated with the development of that fold. For example, west verging folds are indicative of west directed transport. As mentioned in Chapter 4, D₂ folds are spatially associated with the boundary and commonly exhibit westward vergence. The kinematics of west-vergent folding is compatible with that determined from the S-C fabric of the RERG. Collectively the west-vergent folds and the S-C fabric provide convincing evidence that east over west tectonic transport occurred along and adjacent to the prebatholithic boundary.

**D₃ Deformation**

D₃ structures (northeast trending folds and crenulations) seem to indicate an end to the east over west compressive simple shear regime that dominated during D₁ and D₂. The orientation of S₃ indicates that the direction of maximum contraction during D₃ lay sub-parallel to the regional S₁ foliation, perpendicular to the northeast-southwest shortening direction indicated by D₁ and D₂ structures. The tectonic significance of northeast-trending structures near Rancho El Rosarito and elsewhere in the Peninsular Ranges (Griffith, 1987; Windh and Griffith, 1987) is not well understood. Analogous late stage (post main phase) structures have been reported from fold-mountain belts worldwide (Ramsay, 1962; Roberts, 1971; Naha and Halyburton, 1974; Tobisch
and Fiske, 1976; Henry, 1986). It appears that late stage, orogen parallel shortening is a common, but poorly understood, phenomenon of many fold-mountain belts.

Tobisch and Fiske (1976) have suggested that orogen parallel shortening may be a fundamental late stage process in the development of certain orogenic belts. Based upon observations of conjugate folds and cleavages in the central Sierra Nevada, they invoke a model involving elastic recovery following intense contraction normal to the mountain belt. According to this model, shortening normal to the mountain belt produces a slaty cleavage and is accompanied by upward as well as parallel extension. As this contractional event diminishes, "elastic recovery" parallel to the belt induces shortening in that direction. This model implies that the formation of slaty cleavage, and the subsequent late stage crenulations represent a continuous process of deformation. Paterson (1989) has reevaluated the minor structures described by Tobisch and Fiske (1976) and concludes that their orientation and style are not fully explained by the elastic recovery model. He suggests that these structures may have formed from local causes that reflect late events within the orogenic belt. He points out that they generally occur along ductile shear zones and suggests that this relationship may be a
textural one; highly sheared fault rocks provide the appropriate anisotropy for later fold development.

Henry (1986) proposed an alternative model to explain the presence of northeast-trending structures in Baja California and western mainland Mexico. He points out that such structures indicate crustal shortening parallel to the northwest-trending continental margin and plate boundary. He suggests that the indicated northwest directed shortening must have been the consequence of oblique convergence between the north American and Farallon plates.

\textbf{D}_4 \textit{Deformation}

\textit{D}_4 is indicated by a map scale flexure of the Eastern Metasedimentary Sequence in the northern portion of the field area. From reconnaissance inspection and aerial photography it is evident that this flexure is the consequence of the local deflection of the regionally developed \textit{D}_1 fabric around a post-tectonic pluton that crops out immediately to the north of the field area (Figure 25).
CHAPTER VII

TECTONIC MODELS

Introduction

There are potentially many geologic situations that can produce the regional penetrative deformation seen within the Peninsular Ranges batholith. Most models invoke either internally or externally imposed deformation processes. External deformation models suggest that the structural fabrics common to arc regions are the consequence of regional crustal scale stresses related to plate tectonic collisional events. Internal deformation models alternatively propose that these structural fabrics are simply a manifestation of magmatic processes within the batholith. Four potential deformation producing models are considered in the following discussion.

External Deformation Models

Dual Arc/Collision

Gastil and others (1978, 1981) proposed an arc-continent collision model for the Peninsular Ranges
batholith. According to their model (Figure 26), a dual, normal-polarity subduction system had developed along the western margin of North America by Early Jurassic time. This system produced two volcanic arcs, an oceanic arc represented by the Alisitos Formation-Santiago Peak Volcanics and a continental arc represented by Jurassic-Cretaceous volcanic and plutonic rocks of central Sonora. Between the two arcs, the western margin of North America shed a thick wedge of clastic debris that is now represented by the Peninsular flysch rocks. By the Early Cretaceous, the oceanic arc collided with and was sutured to the western edge of North America. The Peninsular flysch rocks were trapped between these colliding masses and consequently underwent penetrative, regional deformation. Upon collision, convergence ceased along the eastern subduction zone, resulting in an increase in convergence along the western subduction zone. This increase in convergence velocity resulted in a shallower subduction angle, moving the axis of plutonism inland, across the suture zone. Eventually, post-tectonic plutons "stitched" together and largely obliterated the suture zone.

Back Arc Collapse

Griffith (1987) proposed an alternative collision model for the Cretaceous evolution of Peninsular
Figure 26. Dual Arc/Collision model (from Gastil and others, 1978).
California (Figure 27). In this model, normal polarity subduction produced Alisitos volcanism within a fringing island arc. The Alisitos arc was separated from the continent by a narrow ensialiac back arc basin. Circa 97 m. y. ago, increased convergence velocities, as predicted by plate motion hot spot studies (Engerbretson and others, 1985), resulted in shallowing of the subduction angle. The shallow subducting plate interacted with the base of the overlying plate causing the collapse of the arc against the continent and regional D$_1$ deformation.

**Internal Deformation Models**

**Forcible Pluton Emplacement**

Batholiths are regions where great volumes of plutonic rock have been added to the crust. Gastil (1979) suggested that such volumetric additions are made possible by lateral compression of the pre-existing host rocks. Within the zone of pluton emplacement (Figure 28), the host rocks are caught between ascending and expanding, near vertical, diapirs resulting in a steep foliation, a near vertical lineation and tightly oppressed, steeply plunging folds.

As the zone of pluton emplacement is volumetrically expanded, the overlying supracrustal rocks must extend laterally. Extension in the supracrustal rocks manifests
Figure 27. Back arc collapse model of the Cretaceous evolution of the Baja California peninsula (from Griffith, 1987).
Figure 28. Conceptual model of batholithic emplacement (from Gastil, 1979). This model suggests that regional tectonite fabrics in batholithic regions are the consequence of the forcible emplacement of plutons within the zone of lateral compression.
itself as horsts and grabens which develop above a plane of decoupling. The plane of decoupling is a plane of low angle normal faulting along which the supracrustal rocks slide away from the isostatically rising orogenic belt. Thus, this model suggests a deformational scenario that simultaneously produces contractional and extensional structures within different levels of the magmatic arc. The important implication is that contractional structures in batholithic regions do not necessarily indicate regional crustal shortening, associated with plate collisional events.

The concept of batholiths being extensional environments, with magma emplacement responsible for deformation of the wall rocks, has been further considered by Tobisch and others (1986). They describe steeply west-dipping Mesozoic, volcanic sequences within roof pendants of the eastern Sierra Nevada. Superimposed on the tilted volcanic sequences are a bedding parallel slaty cleavage and a steeply plunging extension lineation. This tectonite fabric was considered by several authors to have formed by regional contraction related to accretionary collisional processes (external deformation) during the Late Jurassic, Nevadan orogeny (Bateman and Eaton, 1967; Schweickert and Cowan, 1975; Schweikert, 1981; Schweikert and others, 1984; Day and
others, 1985). However, Tobisch and others (1987) point out a number of enigmas with the proposed collisional model. Most notably, the collision model does not account for the fact that parts of the deformed sections are younger than the Late Jurassic. They argue that there are no documented post-Nevadan collisional events, and therefore, they were led to consider the dynamic processes within the Cretaceous batholith (internal deformation) as the probable cause of deformation.

Tobisch and others (1987) conceive a two stage deformational sequence involving; (1) tilting of the volcanic sequence along listric normal faults during regional extension (related to magmatic tumescence), and (2) subsequent imposition of tectonite fabrics as rising and expanding magmatic sills intrude the tilted volcanics. The tectonite fabric being facilitated by downward return flow and stretching of the host rock relative to the rising plutons.

Gravity Tectonics

Eskola (1948) was the first to describe domical bodies of gneiss covered by a mantle of metasedimentary and metavolcanic rock. These tectonic structures, which he called "mantled gneiss domes", have since been recognized in orogenic belts worldwide (Tilton and others, 1958; Wetherhill and others, 1962; Faul and
others, 1963; Thompson and others, 1968; Naylor, 1969; 
Zen and others, 1968). Haller (1971) demonstrated the 
complex forms exhibited by gneiss domes, and showed that 
the core gneisses sometimes diapirically penetrate the 
overlying cover rocks (Figure 29). Ramberg (1967) 
believed that gravitational instabilities, due to density 
differences between the cover and the basement, provide 
the motive force for gneiss dome formation. Using 
centrifuge techniques, he was able to produce 
experimental models that were remarkably similar to 
natural examples (Figure 30). From such pioneering 
stoudies, it has been generally well established that due 
to gravitational instabilities, the less dense core 
gneisses rise and sometimes diapirically mushroom into 
the overlying mantle complex, probably during regional 
metamorphism.

Gastil and others (1975), presented a hypothetical 
cross section across the Peninsular Ranges batholith 
(Figure 31) that is reminiscent of gravity tectonic 
processes. They recognize four metamorphic zones; (1) a 
zone of unmetamorphosed to slightly metamorphosed rock 
(2) a zone of low-grade metamorphic rock (e.g. slates, 
phyllites), (3) a zone of medium-grade metamorphic rock 
(e.g. schists, amphibolites) and (4) a zone in which the 
preametamorphic fabric has been totally destroyed. They
Figure 29. Examples of gneiss domes, or diapirs of granitoid gneisses rising into overburden of crystalline schists (from Haller, 1971).
Figure 30. Centifuged model of dome of silicone putty containing folded and ruptured sheets of modelling clay, having penetrated a layered overburden of painters putty. Note rim synclines and inversion of strata (from Ramberg, 1981).
Figure 31. A hypothetical cross section of the peninsula showing the relation of infrastructural and suprastructural (metamorphic-tectonic) zones (from Gastil and others, 1975).
indicate that zones 1 and 2 represent the rigid domain of the crust (the suprastructure), zone 4 represents the plastic infrastructure, and zone 3 represents a transitional zone. They envision that during pluton emplacement and regional metamorphism the infrastructure deformed plastically and intruded the overlying suprastructure. Gastil and others (1975, p. 28) indicate that, "in places along the sides of the infrastructural rise is a zone of mylonitization that marks the boundary between zones 3 and 4." Such a zone of mylonitization would be the RERG (Gastil, pers. comm.)

Since the advent of plate tectonic theory, the concept of gravity (vertical) tectonics has been overshadowed by ideas based on horizontal movements of the Earth's plates. This has resulted in competition between two opposed schools of thought: (1) orogenesis is a gravity driven diapiric process, or (2) orogenesis results from horizontal compression driven by the convergence of lithospheric plates. However, horizontal and vertical tectonics should not be considered as mutually exclusive processes. Rather, it may be beneficial to consider the relative role of vertical tectonics within the larger plate tectonic setting. Expanding upon this idea, a gravity/plate tectonic model is here proposed for the Mesozoic evolution of the
Peninsular Ranges batholith (Figure, 32). According to this model, a thick wedge of cratonally derived detritus (Peninsular flysch terrane) had accumulated off the western margin of North America by Early Cretaceous time. Normal polarity subduction was producing a continent fringing magmatic arc by about 120 m.y. ago. Within this arc system, relatively low density granitoids were emplaced within the Peninsular terrane sedimentary wedge, while their volcanic equivalents were accumulating above it (pre orogenic arc). At approximately 100 m.y. ago, temperatures had reached a critical threshold within the zone of pluton emplacement. Concurrent with regional metamorphism, the hot and less dense zone of pluton emplacement buoyantly rose and diapirically mushroomed into the overlying volcanic mantle (orogenic arc). During this orogenic event, the highly mobile infrastructural rocks attained there penetrative L-S tectonite fabric. Continued subduction during the late Cretaceous spawned post-tectonic plutons that intruded and obscured the Peninsular Ranges gneiss dome complex (post orogenic arc). Subsequent uplift, erosion and formation of the Gulf of California produced the present configuration seen in the Peninsular Ranges.
Figure 32. Gravity/Plate tectonic model for the Mesozoic evolution of the Peninsular Ranges batholith.
CHAPTER VIII

DISCUSSION AND CONCLUSION

Introduction

From all the available data it is apparent that a major, regionally developed, deformational episode ($D_1$) occurred within the Peninsular Ranges batholith circa 100 m.y. ago. In areas where detailed structural studies have been conducted, the evidence suggests that this deformation was a consequence of a northeast-southwest directed contraction that was characterized by east over west tectonic transport. What is not readily apparent is the cause of this deformation and the tectonic setting under which it occurred. Is the prebatholithic boundary a suture zone that formed when the Jurassic-Cretaceous arc collided with western North America? Is the regional $D_1$ deformation the consequence of this collisional event or is it a manifestation of internally imposed forces related to magmatic and metamorphic processes within a dynamically evolving batholith? In this chapter these fundamentally important questions are discussed with reference to the available data.
Discussion

Evidence For a Suture Zone

The existence of the proposed early Cretaceous suture is largely based upon lithologic, geochemical, and geophysical variations transverse to the long axis of the batholith. The concept of the suture zone was originally based upon the distinct change in host rock lithologies across the prebatholithic boundary (Gastil and others, 1978, 1981). Other workers have shown abrupt changes in the batholithic rocks as well. Todd and Shaw (1985) delineated a boundary in southern California that shows the westernmost extent of S-type granites (Chappel and White, 1974). They show that this boundary, as well other boundaries which delineate gravity (Oliver, 1980), age, and isotopic (Silver and others, 1979) contrasts, are close to and run parallel with the prebatholithic boundary. Most workers believe that these boundaries reflect a change in source rock from primitive, oceanic crust on the west to continental crust (or at least continentally derived sediments) to the east. Todd and Shaw (1985) and Todd and others (1988) suggested that these boundaries are evidence for the suture and that the contractional structures within the Early Cretaceous plutons and their wallrocks were the consequence of the proposed collisional event. Unpublished critics of the
collisional model generally argue that the prebatholithic and batholithic boundaries are not definitive evidence of a suture and that contractional structures within the batholith are the result of the forcible emplacement of plutons.

If the Jurassic-Cretaceous arc was thrust beneath the western edge of North America, then the structural fabric along the prebatholithic boundary (proposed suture zone) should record significant east over west simple shear. The only two detailed structural analyses of rocks along this boundary (this study and Griffith, 1988) do in fact indicate the occurrence of east over west simple shear. Thus, the available structural data is compatible with, but does not prove, the proposed accretionary event.

Many other crustal sutures throughout the world contain bits of oceanic crust (ophiolite). In these settings ophiolites are generally interpreted to be the remnants of a subducted oceanic plate. In the Peninsular Ranges batholith there are a few localities where metamorphosed ultramafic rock crops out along the proposed suture zone (Gastil and others, 1978). If these meta-ultramafics are in fact remnants of ophiolites, then their presence is strong evidence for the existence of the suture.
Did Forcibly Emplaced Plutons Produce The Regional Deformation?

The forcible emplacement and ballooning of plutons is another idea that might explain the regional D$_1$ deformation within the Peninsular Ranges batholith. However no one has demonstrated this relationship at a specific site. In other batholithic regions throughout the world there have been several documented examples of deformation related to forceful pluton emplacement (Pitcher and Berger 1972; Barriere 1977; Sylvester and others, 1978; Bateman 1985; Brun and Pons, 1980). Bateman (1985) established four criteria by which pluton related deformation can be identified: (1) The aureole foliation is penetrative near the contact, decreases in intensity away from the contact, and disappears within a few kilometers from the contact. (2) The aureole foliation is parallel to the pluton contact, forming elliptical, almost completely closed trend lines. (3) The aureole foliation is parallel to and continuous with the foliation of the pluton. (4) The microstructures of the aureole indicate that the contact metamorphic minerals grew synkinematically with the development of the foliation. Griffith (1987) used these criteria to conclude that the regional D$_1$ deformation in the Sierra Calamujae area cannot be attributed to pluton
emplacement.

In the Rancho El Rosarito area, pluton related deformation is unlikely. In other regions of the batholith, the regional fabric generally dips steeply to the east. It is conceivable that such steep fabrics could have been caused by vertically ascending and ballooning plutons. However, near Rancho El Rosarito the regional $D_1$ fabric is moderately shallow, on average dipping 40 degrees to the east. It is considered unlikely that such a shallow fabric could have been produced by plutonic processes.

Because magmatic arcs occur along convergent plate boundaries, many geologists believed that they are commonly regimes of shortening. This belief was based on the assumption that a subducting plate rolls over a hinge and slides down a slot that is fixed in the mantle. However, the conventional wisdom is that the hinge zone of the subducting plate retreats (rolls back) as the overriding plate advances (Molnar and Atwater, 1979). Advance of the overriding plate is accomplished by splitting of the magmatic arc (Hamilton, 1988) and by sea floor spreading behind the arc (Karig, 1972). Thus the typical regime in an overriding plate above a sinking slab is one of extension, not shortening (Hamilton, 1988). Busby-Spera and Boles (1986) suggested that
crustal extension occurred in the Alisitos forearc during the Albian-Aptian. If the crust was extending in the arc region as well, then it seems unlikely that the batholiths plutons were being forcibly emplaced. Instead, they may have simply occupied space produced by subduction related crustal extension.

Much more research needs to be done concerning the question of pluton related deformation. If plutons are the cause of the regional D₁ deformation in the Peninsular Ranges batholith, then it should be easy to demonstrate increasing strain towards their contacts. Field studies of this type would make an important contribution to supporting or refuting this mechanism of deformation. At this time however, there is no evidence to support the conceptual hypothesis that regional fabrics can be produced from forcibly emplaced plutons.

Further Consideration for the Gravity Tectonic Model

In western Baja California, the Albian-Aptian age volcanic rocks of the Alisitos Formation are considered to be the surficial equivalents of the Albian-Aptian age plutons (120-110 Ma.) that intrude them (Silver and others, 1979). East of this belt slightly younger (Albian-Cenomanian) plutons (110-90 Ma.) intrude the Lower Cretaceous (?) and older rocks of the metasedimentary terranes. Something that is rarely
considered is that these plutons must have had surficial volcanic equivalents above them as well. Therefore, it seems reasonable that a continuous, eastward younging, volcanic unit (that is now largely eroded away) once stretched across the entire Peninsular Ranges batholith. Significantly, the paleontologic data from the Peninsular Ranges suggest that the western metavolcanic rocks are slightly younger than the adjacent metasedimentary rocks to the east. In southern California, Late Jurassic metavolcanic rocks are adjacent to Triassic to Jurassic metasedimentary rocks. In Baja California (south of the Agua Blanca fault) Albian-Aptian (medial Cretaceous) metavolcanic rocks are juxtaposed against Ordovician to Early Cretaceous metasedimentary rocks. Thus, paleontologic data do not preclude the possibility that the western metavolcanic rocks represent a younger and depositionally higher part of a continuous late Paleozoic and Mesozoic section.

Considering the above arguments, it might be more correct to consider the prebatholithic boundary as the upturned contact between shallow and deep rocks of the batholith rather than the contact between western and eastern domain rocks. Uplift of the eastern side of the batholith along ductile east over west thrust faults (perhaps as a consequence of infrastructural diapirism),
and deep erosion could have produced the sharp contrast presently seen across the prebatholithic boundary.

**Conclusions**

Structural, metamorphic, and geochronologic data from the Rancho El Rosarito area indicate that a major deformational episode, characterized by east over west ductile thrusting, occurred around 100 m.y. ago. Other structural studies within the Peninsular Ranges suggest that this deformation was regionally developed. As previously discussed, there is considerable controversy concerning the cause of this deformation. It is concluded that data presented in this thesis and in other related studies are compatible with but, do not prove, (1) the collisional models of Gastil and others (1978, 1981) and Griffith (1987), (2) the non-collisional, gravity tectonic model, and (3) does not support the proposal that the regional deformational fabric is a consequence of forcible pluton emplacement.

The controversial issue of whether the regional D₁ fabric is the consequence of internally or externally imposed forces cannot confidently be answered at this time. However, if internal forces were responsible, then it seems most likely that the cause of deformation was the buoyant rise of the batholith's infrastructure during
regional metamorphism and plutonism (gravity tectonics) and not the consequence of forcibly emplaced plutons.
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APPENDIX A

Petrographic and Hand Sample Descriptions

Sample 96  Quartzite (metachert)

Hand Sample Description

Light greenish gray, thinly bedded, finely laminated, well lineated, well indurated, very fine-grained.

Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>69%</td>
</tr>
<tr>
<td>Chloritoid</td>
<td>28%</td>
</tr>
<tr>
<td>Calcite tr.</td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>03%</td>
</tr>
</tbody>
</table>

Textures:

Granoblastic quartz (recrystallized mosaic, .02-.25mm.), alternating chloritoid, carbon, coarse and fine grained quartz layers define a well developed banding, chloritoid is preferentially aligned parallel to banding.

Sample 23  Quartzite (metachert)

Hand Sample Description

Dark gray to black, finely laminated, tightly folded, very well indurated, extremely fine grained

Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>65%</td>
</tr>
</tbody>
</table>
Sericite 11%
Carbon 19%
Hematite 01%
Calcite 04%

Textures:

Granoblastic quartz (recrystallized mosaic .01-.1 mm.), carbon disseminated and localized in well developed laminae.

**Sample 11-29-86. 7 Lapilli Tuff**

**Hand Sample Description**

light gray stretched lapilli as large as 30 mm. and feldspar phenocrysts in black fine grained matrix, strongly foliated.

**Petrographic Description**

**Constituents:**

Hornblende 26%
Quartz 20%
Biotite Tr.
Plagioclase 15%
K- Feldspar 37%
Epidote 02%

Textures:

Granoblastic quartzo feldspathic lapilli and coarse plagioclase phenocrysts within an anastomozing hornblende rich matrix, clast supported, epidote alteration of feldspars.

**Sample 116 Quartzite (metachert)**

**Hand Sample Description**

siliceous, well indurated and foliated, extremely fine grained, weathers to brownish gray.

**Petrographic Description**

**Constituents:**

Quartz 79%
Biotite  14%
Opaques  07%

Textures:

very fine grained (.02-.15 mm) granoblastic quartz (recrystallized mosaic), preferential alignment of biotite defines foliation.

Sample 75  Ash Fall Tuff

Hand Sample Description

light gray, weathers to light tan, extremely well indurated, cherty texture, well bedded (see figure 5)

Petrographic Description

Constituents:

Groundmass  78%
Quartz  10%
Calcite  12%

Textures:

Siliceous, cryptocrystalline groundmass, randomly oriented calcite and quartz phenocrysts, many calcite phenocrysts exhibit characteristic rhomboid shape, quartz phenocrysts are commonly polycrystalline.

Sample 286  Garnet Mica Schist

Hand Sample Description

Reddish brown, well foliated, lineated and indurated, garnet porphyroblasts as large as 1 cm.

Petrographic Description

Constituents:

Quartz  26%
Plagioclase  19%
K-Feldspar  16%
Biotite 08%
Muscovite 11%
Sillimanite 05%
Staurolite 03%
Opaques 08%
Hematite 05%

Textures:

Flattened, quartzofeldspathic recrystallized mosaic (.02-.9 mm.) and preferentially aligned micas and sillimanite define a well developed foliation.

Sample 1-12-87, 8 Granofels

Hand Sample Description

Cream colored, well indurated and bedded, finely laminated, very fine grained, very fine visible hornblende.

Petrographic Description

Constituents:

Quartz 28%
Hornblende 11%
Epidote 20%
Biotite tr.
Plagioclase 25%
K-Feldspar 16%

Textures:

Recrystallized, quartzofeldspathic mosaic (.02-.33 mm.), subparallel alignment of hornblende and biotite define the foliation.

Sample 11-30-86, 4 Basalt Porphyry

Hand Sample Description

Black on fresh surface, weathers to medium gray, well indurated, randomly oriented plagioclase phenocrysts as large as 2mm.
Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>14%</td>
</tr>
<tr>
<td>Quartz</td>
<td>10%</td>
</tr>
<tr>
<td>Epidote</td>
<td>05%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>tr.</td>
</tr>
<tr>
<td>Chlorite</td>
<td>09%</td>
</tr>
<tr>
<td>Groundmass</td>
<td>62%</td>
</tr>
</tbody>
</table>

Textures:

Randomly oriented plagioclase phenocrysts in dark greenish brown fine grained matrix, matrix supported.

Sample G-28 Lapilli Tuff

Hand Sample Description

white, preferentially aligned, angular lapilli as large as 10 mm. within black aphanitic matrix, matrix supported, very well indurated, weathers to reddish brown.

Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>19%</td>
</tr>
<tr>
<td>Hornblende</td>
<td>tr.</td>
</tr>
<tr>
<td>Epidote</td>
<td>14%</td>
</tr>
<tr>
<td>Chlorite</td>
<td>06%</td>
</tr>
<tr>
<td>Quartz</td>
<td>07%</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>16%</td>
</tr>
<tr>
<td>Groundmass</td>
<td>38%</td>
</tr>
</tbody>
</table>

Textures:

Plagioclase dominated lapilli are preferentially aligned in chlorite, epidote, plagioclase matrix.

Sample 274 Garnet Gneiss

Hand Sample Description
Very well foliated and lineated, gneissic structure, garnet porphyroblasts as large as 1 mm., well indurated.

Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>38%</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>09%</td>
</tr>
<tr>
<td>K- Feldspar</td>
<td>18%</td>
</tr>
<tr>
<td>Biotite</td>
<td>30%</td>
</tr>
<tr>
<td>Muscovite</td>
<td>tr.</td>
</tr>
<tr>
<td>Garnet</td>
<td>01%</td>
</tr>
<tr>
<td>Epidote</td>
<td>04%</td>
</tr>
</tbody>
</table>

Textures:

Coarse grained (.1-1 mm.) flattened, quartzofeldspathic mosaic. Preferentially aligned biotite defines the well developed foliation.

Sample X Garnet Mica Schist

Hand Sample Description

Visible biotite and muscovite, well foliated and lineated, dark colored.

Petrographic Description

Constituents:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>03%</td>
</tr>
<tr>
<td>Biotite</td>
<td>46%</td>
</tr>
<tr>
<td>Muscovite</td>
<td>19%</td>
</tr>
<tr>
<td>Garnet</td>
<td>09%</td>
</tr>
<tr>
<td>Sillimanite</td>
<td>tr.</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>02%</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>14%</td>
</tr>
</tbody>
</table>

Textures:

Flattened quartzofeldspathic mosaic (.05-.8 mm) and preferentially aligned mica defines the well developed foliation, Garnet porphyroblasts.
Sample 73  Basalt Porphyry

Hand Sample Description

Randomly oriented plagioclase phenocrysts as large as 4 mm. in black aphanitic matrix, weathers to medium gray, well indurated.

Petrographic Descriptions

Constituents:

- Plagioclase 65%
- Epidote 07%
- Muscovite 02%
- Chlorite 18%
- Opaques 08%

Textures:

Poorly to moderately well developed trachytic texture.

Sample 218  Tonalite

Hand Sample Description

Leucocratic, medium grained, holocrystalline granitoid, poorly to moderately well developed foliation.

Petrographic Description

Constituents:

- Plagioclase 54%
- Quartz 34%
- Biotite 06%
- Hornblende 01%
- K-Feldspar 05%

Textures:

Fine to medium grained, sub- to anhedral, equigranular, sub parallel alignment of biotite defines poorly to moderately well developed foliation.
Sample 49  Garnet Mica Schist

Hand Sample Description

Coarse biotite and muscovite, garnet porphyroblasts as large as 5 mm., dark colored, well foliated.

Petrographic Description

Constituents:

- Biotite 50%
- Muscovite 08%
- Garnet 12%
- Quartz 10%
- Plagioclase 02%
- Sillimanite tr.
- K-Feldspar 15%
- Opaques 03%

Textures:

- Porphyroblastic, poikiloblastic garnets, parallel alignment of micas define a well developed foliation.

Sample 31  Glomeroporphyritic Dacite

Hand Sample Description

White on fresh surface, weathers to reddish tan, aphanitic, massive, well indurated.

Petrographic Description

Constituents:

- Plagioclase 09%
- Quartz 08%
- Epidote tr.
- Opaques 01%
- Groundmass 82%

Textures:

- Pilotaxitic groundmass composed of feldspar microlites and quartz, glomeroporphyritic, sub- to euhedral plagioclase phenocrysts
Sample 293  Pillow Basalt

Hand Sample Description

Greenish dark gray, aphanitic, amygdaloidal (calcite), pillow structures (?), interstitial calcite, well indurated, well developed cleavage, well indurated.

Petrographic Description

Constituents:

- Calcite 07%
- Epidote 02%
- Plagioclase 01%
- Chlorite 06%
- Opaques 02%
- Groundmass 82%

Textures:
Dark greenish black cryptocrystalline groundmass dissected by numerous calcite and chlorite veins and amygdules.

Sample 63  Garnet Mica Schist

Hand Sample Description

Garnet porphyroblasts as large as 15 mm., well foliated and lineated.

Petrographic Description

Constituents:

- Quartz 32%
- Biotite 21%
- Muscovite 02%
- Plagioclase 36%
- Garnet tr.
- Sillimanite tr.
- K-Feldspar 08%
- Opaques 01%

Textures:
Recrystallized quartzofeldspathic
mosaic (.05-.7 mm.), preferentially aligned biotite define an anastamosing foliation.

Sample 193 Garnet Gneiss

Hand Sample Description

Euhedral garnet porphyroblasts as large as 3 mm., gneissic texture, well foliated and lineated, well indurated, visible biotite and muscovite.

Petrographic Description

Constituents:

- Quartz 26%
- Biotite 48%
- Muscovite 03%
- Garnet 15%
- Plagioclase 08%
- K-Feldspar 15%

Textures:

Alternating quartzofeldspathic (recrystallized mosaic, .02-.2 mm.), and biotite rich layers, preferentially aligned micas define a well developed foliation, poikiloblastic, flattened garnets.

Sample 114 Quartz Mica Schist

Hand Sample Description

Visible muscovite and biotite, light gray, weathers to reddish gray, well foliated and lineated.

Petrographic Description

Constituents:

- Quartz 35%
- Biotite 10%
- Muscovite 01%
- Hematite 09%
Sillimanite    tr.
K-Feldspar    31%
Plagioclase   10%
Opaques       04%

Textures:
Quartzofeldspathic recrystallized mosaic (.02-.6 mm.), asymmetric mica fish.

Sample 82  Quartz Mica Phyllite

Hand Sample Description
Bluish green, anastomozing cleavage, pervaded by quartz veins.

Petrographic Description
Constituents:
- Quartz      31%
- Plagioclase  12%
- Calcite     43%
- Biotite     03%
- Chlorite    10%
- Muscovite   tr.
- K-Feldspar  01%

Textures:
Strained quartz (shadowy extinction) and plagioclase crystals set in a very fine grained, foliated matrix, Asymmetric plagioclase porphyroclasts are common, extreme grain size variation.

Sample 6  Lapilli Tuff

Hand Sample Description
Light gray tuffaceous lapilli in black fine grained matrix, anastomozing cleavage.

Petrographic Description
Constituents:
Biotite 55%
Quartz 16%
Plagioclase 11%
K-Feldspar 17%
Opales 01%

Textures:

Stretched lapilli comprised of quartzofeldspathic recrystallized mosaic (.02-.05 mm.), preferentially aligned biotite define a well developed foliation.

Sample 163 Quartz Phyllite

Hand Sample Description

Black, well foliated, fine grained, relict sandsize clasts.

Petrographic Description

Constituents:

Quartz 37%
Biotite 07%
Plagioclase 39%
K-Feldspar 09%
Opales 04%
Epidote 02%
Hornblende 02%

Textures:

Quartzofeldspathic recrystallized mosaic (.02-.4 mm.), preferentially aligned biotite defines a well developed foliation.

Sample 127 Andesite Flow

Hand Sample Description

Greenish dark gray, well indurated, visible phenocrysts.

Petrographic Description
Constituents:

- Plagioclase 08%
- Calcite 02%
- Epidote 04%
- Quartz 02%
- K-Feldspar 01%
- Olivine tr.
- Chlorite 02%
- Groundmass 81%

Textures:

Plagioclase and olivine phenocrysts (.3-1 mm) within a very fine grained, well foliated matrix of chlorite, epidote, quartz, and feldspar.

Sample 267  Granodiorite

Hand Sample Description

Medium grained, holocrystalline, granitoid, very well foliated and lineated, S-C fabric, pink.

Petrographic Description

Constituents:

- Quartz 39%
- Plagioclase 42%
- K-Feldspar 10%
- Biotite 08%
- Opaques 01%

Texture:

Holocrystalline, anhedral, inequigranular, distinct grain size reduction in C planes, shaddowy extinction of quartz, myrmekite, preferentially aligned biotite defines a well developed foliation.

Sample 1-29-86, 6  Quartz Phyllite

Hand Sample Description
Siliceous, greenish brown, well indurated, anastomosing foliation.

Petrographic Description

Constituents:

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<td>Chloritoid</td>
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<td>Staurolite</td>
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<td>Opaques</td>
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Textures:

flattened quartzofeldspathic recrystallized mosaic (.02-.5 mm.), foliation is defined by preferentially aligned chloritoid.

Sample 97  Metagabbro

Hand Sample Description

Greenish black, weathers to dark reddish brown, well indurated, primary igneous texture.

Petrographic Description

Constituents:

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<td>Sphene</td>
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Textures:

Holocrystalline, fine to medium grained, inequigranular, primary igneous textures.
Sample Locality Map
APPENDIX B

STRUCTURAL FABRIC DATA

D1 Structural Fabric Elements

S1 (Foliation, n=274)

| 096, 34NE | 153, 38NE | 145, 25NE | 090, 27N |
| 100, 27NE | 105, 24NE | 100, 27NE | 130, 36NE |
| 110, 24NE | 115, 30NE | 120, 38NE | 130, 59NE |
| 105, 34NE | 120, 34NE | 102, 20NE | 135, 39NE |
| 135, 39NE | 125, 14NE | 145, 40NE | 122, 28NE |
| 136, 36NE | 145, 30NE | 130, 30NE | 102, 20NE |
| 152, 38NE | 148, 44NE | 135, 61NE | 125, 30NE |
| 169, 49NE | 158, 40NE | 171, 51NE | 152, 41NE |
| 164, 69NE | 165, 88NE | 168, 69NE | 142, 59NE |
| 121, 41NE | 140, 42NE | 135, 65NE | 147, 53NE |
| 150, 43NE | 142, 52NE | 137, 52NE | 136, 44NE |
| 140, 40NE | 140, 50NE | 142, 40NE | 140, 40NE |
| 140, 50NE | 142, 40NE | 115, 36NE | 155, 41NE |
| 135, 54NE | 120, 56NE | 148, 54NE | 160, 41NE |
| 140, 45NE | 148, 38NE | 130, 35NE | 165, 45NE |
| 165, 41NE | 145, 25NE | 165, 41NE | 150, 72NE |
| 155, 50NE | 150, 40NE | 155, 30NE | 137, 32NE |
| 130, 25NE | 130, 35NE | 100, 65NE | 125, 58NE |
| 135, 50NE | 105, 75NE | 140, 60NE | 140, 65NE |
| 130, 55NE | 145, 48NE | 150, 57NE | 147, 45NE |
| 135, 56NE | 120, 50NE | 100, 45NE | 140, 65NE |
| 160, 30NE | 155, 43NE | 160, 40NE | 145, 70NE |
| 165, 42NE | 165, 65NE | 162, 50NE | 155, 50NE |
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| 145, 56NE | 148, 42NE | 150, 42NE | 160, 40NE |
| 145, 40NE | 130, 24NE | 155, 25NE | 158, 38NE |
| 011, 24NE | 160, 25NE | 140, 51NE | 140, 65NE |
| 156, 46NE | 160, 40NE | 145, 44NE | 160, 68NE |
| 155, 40NE | 155, 41NE | 143, 57NE | 160, 42NE |
| 140, 45NE | 100, 45NE | 150, 62NE | 147, 39NE |
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| 136, 46NE | 120, 42NE | 151, 33NE | 145, 44NE |
| 149, 37NE | 150, 45NE | 142, 36NE | 145, 36NE |
| 130, 29NE | 130, 32NE | 120, 35NE | 139, 29NE |
| 132, 25NE | 127, 35NE | 125, 35NE | 120, 30NE |
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036, 65NW
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S1a (Axial surfaces of D1 folds, n=28)

I11, 51NE 140, 65NE 140, 45NE 160, 25NE
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155, 45NE 150, 35NE 130, 30NE 140, 50NE
145, 40NE 140, 51NE 140, 59NE 132, 54NE
135, 35NE 137, 59NE 130, 56NE 145, 60NE
100, 45NE 120, 45NE 127, 27NE 150, 60NE

F1 (Fold axes of D1 folds, n=20)

38, 020 45, 050 11, 024 32, 036
48, 034 17, 040 32, 060 40, 040
40, 020 42, 030 29, 029 24, 043
52, 038 40, 058 38, 030 32, 051
54, 062 48, 022 48, 070 32, 043

D2 STRUCTURAL FABRIC ELEMENTS

S2, Domain 1 (Axial Surfaces, n=117)

120, 75NE 155, 85NE 170, 80NE 130, 75NE
130, 95NE 135, 80NE 135, 83NE 140, 84NE
148, 80NE 140, 78NE 145, 84NE 139, 75NE
148, 81NE 137, 75NE 135, 75NE 135, 82NE
131, 78NE 125, 75NE 125, 84NE 125, 86NE
125, 70NE 122, 74NE 135, 81NE 135, 84NE
140, 83NE 134, 79NE 125, 84NE 120, 74NE
133, 80NE 126, 76NE 132, 84NE 120, 79NE
129, 84NE 131, 76NE 133, 81NE 137, 78NE
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128, 74NE 132, 86NE 136, 79NE 137, 82NE
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**F₂ Domain 1 (Fold axes, n=35)**

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**S₂ Domain 2 (Axial surfaces, n=24)**

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**F₂ Domain 2 (Fold axes, n=7)**

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**S₂ Domain 3 (Axial surfaces, n=52)**

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**F₂, Domain 6 (Fold axes, n=10)**

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APPENDIX C

GEOCHRONOLOGIC (U/Pb) DATA

ROCK: Rancho El Rosarito gneiss
Lab: Baylor Brooks Institute of Isotope Geology

<table>
<thead>
<tr>
<th>CONCENTRATION</th>
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<th>RADIOGENIC RATIOS</th>
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<tr>
<td>ppm</td>
<td>204Pb 207Pb 208Pb</td>
<td>*206Pb *207Pb *208Pb</td>
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<tr>
<td>SAMPLE U Pb</td>
<td>206Pb 206Pb 206Pb</td>
<td>238U 235U 206Pb</td>
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<tr>
<td></td>
<td>(age) (age) (age)</td>
<td>(age) (age) (age)</td>
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| nm(-1) 405 6.98 | 0.00054 | 0.05669 | 1.3709 | 0.01674 | 1.125 | 0.04872 |
| m(-1) 411 7.33  | 0.000658 | 0.05838 | 1.6366 | 0.01687 | 1.133 | 0.04870 |
| m0 511 10.12    | 0.000995 | 0.06368 | 2.2600 | 0.01767 | 1.195 | 0.04905 |

* Indicates radiogenic lead corrected for blank 206Pb/204Pb = 18.85; 207Pb/204Pb = 15.64; 208Pb/204Pb = 38.29 and initial lead (Stacey and Kramers, 1975, 110 m.y. old model lead: 206Pb/204Pb = 18.536; 207Pb/204Pb = 15.621; 208Pb/204Pb = 38.431).

nm = non-magnetic; m = magnetic at given side tilt on the Franz Isodynamic Separator. Front tilt used was 20 degrees.

Samples were spiked with a 208Pb/235U mixed spike. Dissolution and chemical separations were modified after Krogh (1973). Blank lead averaged 1.0 ng during the course of these analyses.

Data were reduced according to the methods of Ludwig (1984). Uncertainties in 206Pb/235U ratios are 1% and in 207Pb/235U are 2% at the 95% confidence level assuming that the stacy and Kramers initial lead values are accurate for this rock.

Lead ratios were normalized for mass fractionation of 0.1 +/- 0.03% per mass unit based on replicate analyses of NBS lead standards 982 and 983. The uranium ratio was normalized for mass fractionation of 0.12 +/- 0.06% per mass unit based on replicate analyses of NBS uranium standard U-050.

Decay constants used: Lambda U238 = 0.000155125 and Lambda U235 = 0.00098485 decays per m.y. (Jaffey and others, 1971).
REFERENCES CITED


ABSTRACT
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A prebatholithic boundary between a western domain of Jurassic-Cretaceous volcanic arc rocks and an eastern domain of continentally derived flysch trends northwest along the axis of the Peninsular Ranges. A study of the rocks within a 45 square kilometer area near Rancho El Rosarito, Baja California, Mexico (30° 30' N. Latitude), indicates that east over west ductile thrusting occurred along this boundary during the latest Albian.

The main lithologic units in the Rancho El Rosarito area, from west to east, are the "western metavolcanic assemblage" (WMA), the "eastern metasedimentary sequence" (EMS), and the "Rancho El Rosarito gneiss" (RERG). Occurring west of the prebatholithic boundary, the WMA is comprised of Cretaceous age, rhyolitic to basaltic volcanic flows and tuffs. These rocks have been metamorphosed to greenschist facies, exhibit primary igneous textures, and are generally undeformed. Occurring east of the boundary, the EMS is predominantly comprised of clastic sedimentary rocks that have been variably metamorphosed from greenschist to amphibolite facies (metamorphic grade increases towards the east). In sharp contrast to the adjacent WMA, the rocks of the
EMS are pervasively and multiply deformed L-S tectonites. Regional (main phase) deformation produced a northwest-trending, east-dipping, bedding-parallel foliation, a down-dip extensional mineral lineation, and isoclinal folds that are axial planar to the foliation and which have axes parallel to the lineation. Post main phase deformation produced, northwest-trending, steeply east-dipping, westward-vergent folds that occur in several domains near the prebatholithic boundary. Structurally overlying the EMS is the concordantly deformed RERG. It is dominated by pervasively foliated and lineated orthogneisses of granodioritic composition that have been dated by the U-Pb zircon method at 108 Ma. Within the RERG, main phase deformation produced a composite S-C mylonitic fabric that consistently indicates an east-over-west sense of shear.

The abrupt change in lithology and structural style at the prebatholithic boundary suggests that the WMA and the EMS are structurally juxtaposed. Down-dip lineations in the EMS and the RERG suggest that movements were predominantly dip-slip. The eastward increase in metamorphic grade, the west-verging folds, and the S-C fabric all indicate that the east side was thrust over the west side. U-Pb geochronology from the RERG and the nearby, undeformed, Sierra San Pedro Martir pluton
constrain regional deformation to the latest Albian. All lines of evidence are compatible with west directed translation along the prebatholithic boundary during the medial Cretaceous. Deformation may have been the consequence of externally imposed forces related to the accretion of the Jurassic-Cretaceous arc to cratonic North America. Alternatively it may be a manifestation of internally imposed forces related to the dynamic evolution of the batholith.
PLATE 1

GEOLOGIC MAP OF THE RANCHO EL ROSARITO AREA

EXPLANATION

MAP UNITS

Gri

Quaternary Alluvium

Trx

Terrestrial Pleistocene conglomerate (Miocene-T)

Kf

Tomolite (Late Cretaceous)

Kfh

Monterey shale (Late Cretaceous)

Knp

Mixed zone: (multistage megassemblage) and quartz-felsic (Middle Cretaceous)

Kfn

Anhydrite El Rosarito Formation: anhydrite and siltstone (10-70 Myo; 120 M.p.)

Kn

Eocene (multistage megassemblage) and quartz-felsic (Middle Cretaceous)

Kw

Western metavolcanic assemblage; Rayotina to dacitic flows and rhyolite (100-130 Myo)

SYMBOLS

N STRIKE AND DIP OF BEDDING

SC STRIKE AND DIP OF FOLIATION

CT CONTACT

CTC OPERATIONAL CONTACT

FCT CONTACT (THRUJS), BARS ON OVERPRINT SUG

NS DOPPELIMBAD

ET EKERNEDBAD

ST STRUCTURAL DOMAINS

SCALE

1:12,500

LOCATION MAP

CONTOUR INTERVAL

20 METERS

GEOLOGY OF THE RANCHO EL ROSARITO AREA:
EVIDENCE FOR LATEST ALBIAN, EAST OVER WEST,
DUCTILE THRUSTING IN THE PENINSULAR RANGES
CHRISTOPHER WARREN GOETZ  SPRING, 1989