Metamorphic history and structural evolution of the Orocopia Schist in the Gavilan Hills, S.E. California

by

Felix Ruben Oyarzabal

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department: Geological and Atmospheric Sciences

Major: Geology

Major Professor: Carl E. Jacobson

Iowa State University

Ames, Iowa

1996

UMI Number: 9712583

Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Felix Ruben Oyarzabal

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

"A Rock, A River, A Tree
Hosts to species long since departed,
Marked the mastodon,
The dinosaur, who left dried tokens
Of their sojourn here
On our planet floor,
Any broad alarm of their hastening doom
Is lost in the gloom of dust and ages.

But today, the Rock cries out to us, clearly,
forcefully
Come, you may stand upon my
Back and face your distant destiny,

But seek no haven in my shadow,
I will give you no hiding place down here.
....

The Rock cries out to us today,
You may stand upon me;
But do not hide your face".

Maya Angelou
OnThe Pulse Of Morning

TABLE OF CONTENTS

GENERAL INTRODUCTION

The Vincent Chocolate Mountains fault (VCM) system of southern California and southwesternmost Arizona separates an upper plate of Precambrian to Mesozoic igneous and metamorphic rocks of continental affinities from the oceanic Late Cretaceous-early Tertiary Pelona-Orocopia-Rand (POR) Schist (Fig. 1). The POR schist is composed mainly of metamorphosed graywacke with mafic schist, quartzite, marble, and serpentinite as minor rock types. An increase of temperature toward the thrust is a common feature of the POR schist (i.e., inverted metamorphic zonation), with metamorphic grade ranges mostly from lower greenschist facies to oligoclase amphibolite facies, but locally belong to the epidote-blueschist facies . This system has been fragmented and dispersed along the San Andreas fault, and its segments are exposed in a series of antiformal culminations. Mylonitized rocks are present along the contact in some segments of the system. These mylonites range in thickness from meters to hundreds of meters and are located at the base of the upper plate, at the top of the POR schist, or in both units. The various fragments of the VCM fault are considered to be remnants of the original subduction zone along which the POR schist was underplated beneath the North American continent (Ehlig 1968, 1981, Vargo 1972, Haxel & Dillon 1978, Sharry 1981, Jacobson 1983a). Lately, many segments of the VCM fault have been reinterpreted as post-metamorphic structures related to exhumation rather than burial of the POR schist (Frost & Martin 1983, Haxel *et al.* 1985, Dobreck *et al.* 1986, Postlethwaite & Jacobson 1987, Jacobson *et al.* 1988, Goodmacher *et al.* 1989, Bishop & Ehlig 1990, Dillon *et al.* 1990, Jacobson 1990, 1995, Richard & Haxel 1991, Jacobson & Dawson 1995, Jacobson *et al.* 1996).

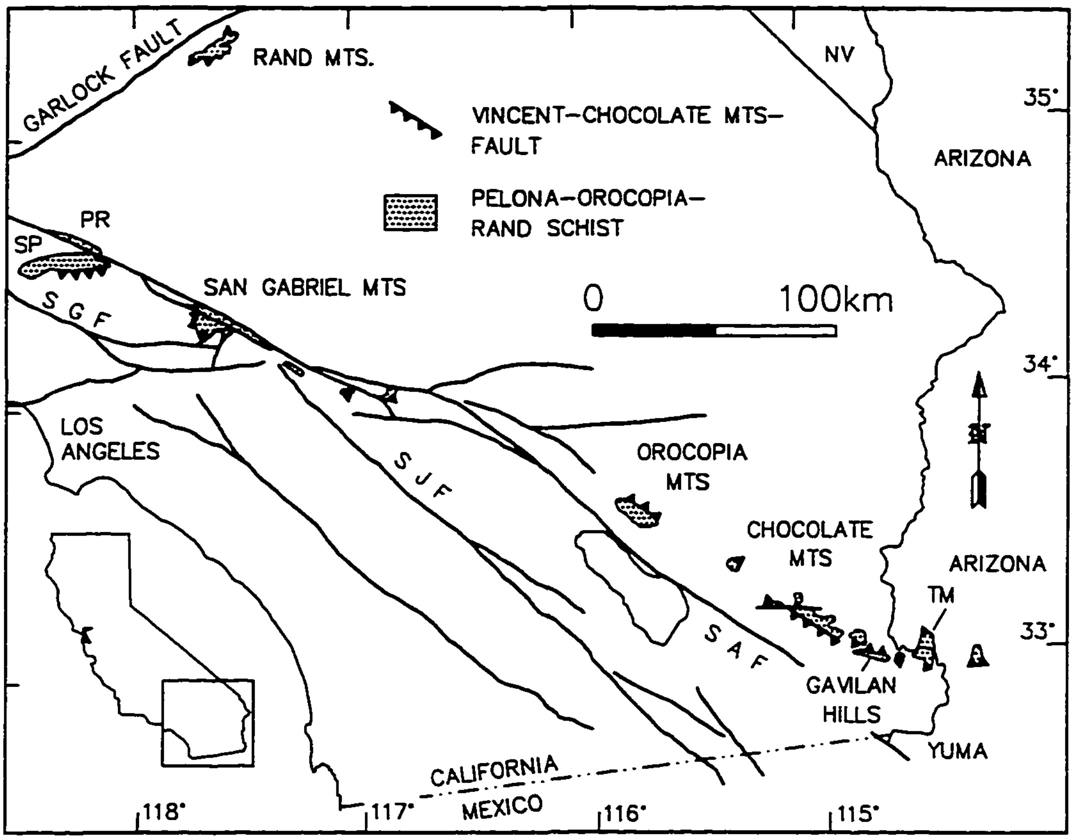

Figure 1. Distribution of the Pelona-Orocopia-Rand Schist and Vincent-Orocopia-Chocolate Mountains fault in southern California. Additional occurrences of the schist are located to the northwest and southeast. The figure follows convention by using barbs to ornament the faults. However, many of the structures have probably been reactivated as normal faults. PR, Portal Ridge; SP, Sierra Pelona; SAF, San Andreas fault; SGF, San Gabriel fault; SJF, San Jacinto fault; TM, Trigo Mountains.

Characterization of the Problem

A long-standing problem of southern California geology is the tectonic significance of the VCM fault and its bearing on the regional paleogeography at the time of formation of the POR schist. Two different models have been proposed to account for the origin of the VCM fault and the POR schist. The first model is based on the NE sense of transport of upper plate rocks on several segments of the VCM fault, and proposes that the POR schist was formed in an ensimatic marginal basin similar to the present Gulf of California (Ehlig 1981, Vedder *et al.* 1983, Haxel & Tosdal 1986, Dillon *et al.* 1990). Closure of this basin was responsible, in this model, for the metamorphism and deformation of the POR schist (Fig. 2a). This model requires a terrane boundary NE of the present outcrops of the POR schist, a boundary that has yet to be recognized (Burchfiel & Davis 1981, Powell 1981)

A second model (Fig. 2b) considers that the schist was metamorphosed in an eastward-dipping, low-angle subduction zone at the border of the North American continent. In this model the schist represents an extension of the Franciscan complex and the NE movement direction of upper plate rocks is related to a late phase of deformation (Crowell 1968, 1981, Yeats 1968, Burchfiel & Davis 1981, Dickinson 1981, Sharry 1981, Hamilton 1987, 1988; Barth 1988).

The Gavilan Hills represent a key exposure of the POR schist in southern California because most of the data suggesting NE transport of upper plate and used to support the marginal basin model were obtained from this area. The Chocolate Mountains fault in the Gavilan Hills has been considered as the original "thrust" along which the POR schist was subducted and metamorphosed, making this the ideal place to study the relations between

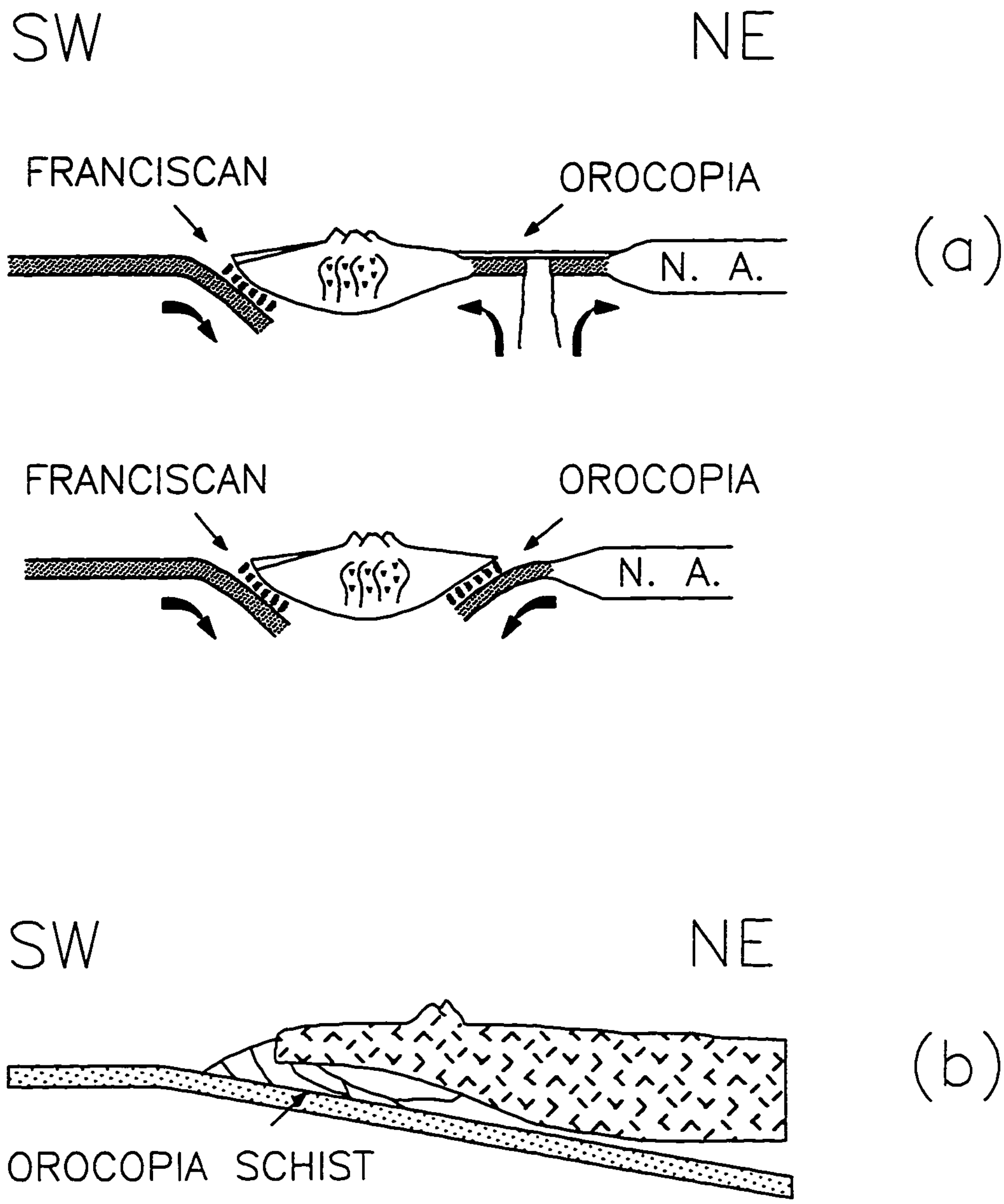

Figure 2. Schematic diagrams for the two tectonic models for the POR Schist.
a) Collisional model, after Jacobson (1980). b) Franciscan Complex type model.

POR schist and upper plate, and test the validity of the proposed tectonic models.

Regional Variation of the VCM Fault

Outcrops of the VCM fault system and the POR schist show a wide range of structural features and contact relations. A brief description of the most important exposures of VCM fault and POR schist will illustrate the differences, and help with comparison among them. The San Gabriel and Orocopia Mountains, the Sierra Pelona, and the Gavilan Hills were close to each other prior to offset by the San Andreas fault. The POR schist in the Rand Mountains is located along the Garlock fault, and its spatial and temporal relationship with other bodies of POR schist is not well understood.

San Gabriel Mountains

In the eastern San Gabriel Mountains, Ehlig (1958, 1981) first described the Vincent "thrust," indicating the subparallelism of foliation, fold axes, and stretching lineation between the fabric of the Pelona Schist and a mylonite located at the base of the upper plate. He also noted an inverted metamorphic zonation in the schist as well as a concordance of metamorphic facies between the mylonite zone and the schist below. These characteristics have been cited as evidence that faulting was contemporaneous with metamorphism in the Pelona Schist, a conclusion that has been extended to the whole system. A continuous trend in composition between calcic amphibole in the schist and amphibole rims in the mylonite corroborates the original character of this segment of the VCM fault (Jacobson 1995, 1997). Based on the sense of overturning of a synformal structure in the POR schist underneath the upper plate (the Narrows synform), Ehlig (1958) deduced a NE direction of transport for the upper plate (Fig 3). His interpretation about the sense of movement has been criticized because it assumes that the axis of the Narrows synform trends perpendicular to the direction of overthrusting. This is contrary to what is expected in deep-seated thrusts, where lineation and fold axes are typically parallel to the direction of tectonic transport (Bryant & Reed 1969, Escher & Waterson 1974). A microstructural study of the mylonites demostrated a NW sense of transport for upper plate rocks (Simpson 1986), but interpretation of transport direction is additionally complicated by paleomagnetic evidence of Neogene vertical-axis rotation (Terres & Luyendyk 1985). Jacobson (1980, 1983a, 1983b) defined, on a geometric basis, three fold styles in the POR schist of the San Gabriel Mountains. Style 1 folds are tight, synmetamorphic folds. Style 2 folds are open-to-tight folds that include the Narrows synform and associated minor folds. They are restricted to the POR schist in the 700 m immediately below the thrust. A post-metamorphic arch and its associated kink bands are classified as style 3 folds. Jacobson (1980, 1983a) showed that the axes of style 1 and style 2 folds are subparallel to each other. Based on studies of muscovite composition, he concluded that the different folding styles were produced in a single protracted event, suggesting that the most probable mechanism responsible for those structures was subduction (Jacobson 1984). Similar amphibole and mica K-Ar and $^{40}Ar/^{39}Ar$ cooling ages were obtained for the base of the upper plate and the POR schist (~ 60 Ma; Miller & Morton 1980, Jacobson 1990).

Rand Mountains

In the Rand Mountains, the POR schist (locally named the Rand Schist) crops out in a W-NW trending post-metamorphic antiform and shows an inverted metamorphic zonation

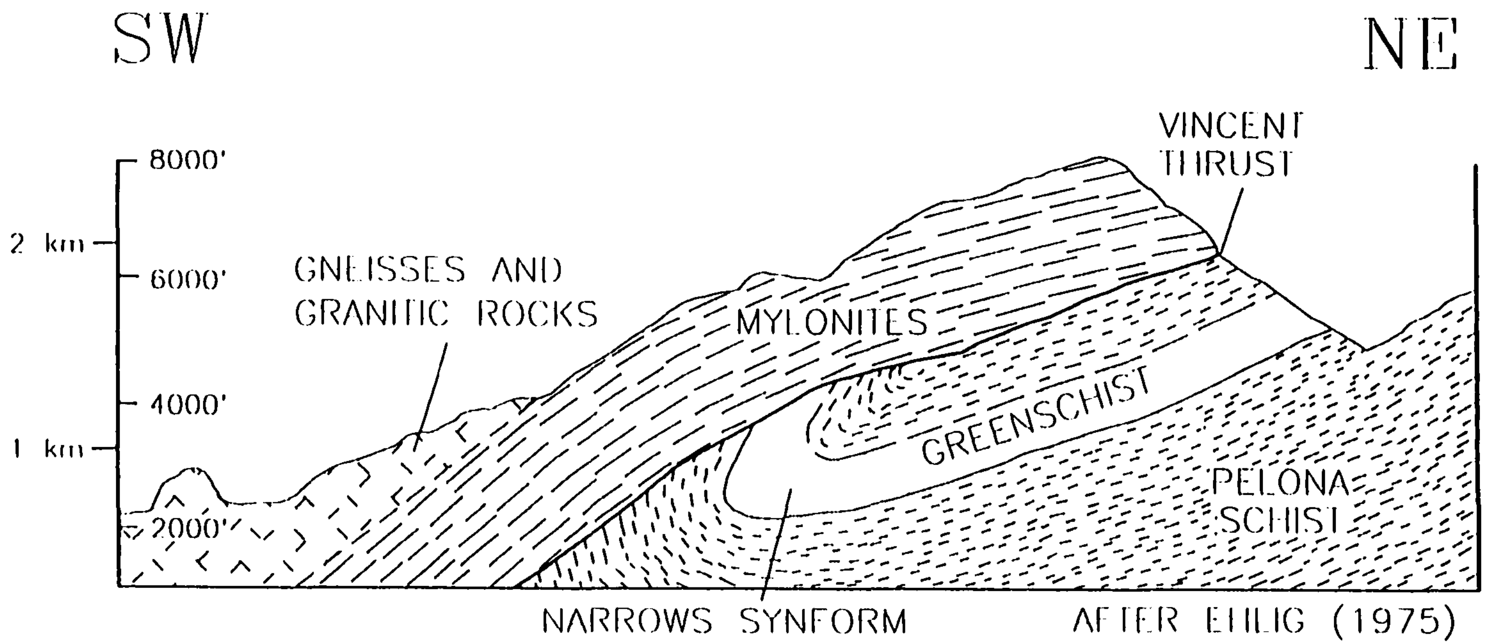

Figure 3. Cross section of Vincent thrust with the Narrows synform in the East Fork area of the San Gabriel Mountains.

from epidote blueschist facies through greenschist and epidote-amphibolite facies to oligoclase-amphibolite facies (Jacobson & Sorensen 1986, Postlethwaite & Jacobson 1987, Jacobson 1995). In the northeastern part of the range, the POR schist is overlain by the Johannesburg gneiss, which contains mylonitic zones parallel to the contact with the schist. In the southwest corner of the range, the Atolia Quartz Monzonite overlies the POR schist along a low-angle, post-metamorphic normal fault according to Silver & Nourse (1986) and Postlethwaite & Jacobson (1987). The structural pattern of the Rand Mountains differs from the San Gabriel Mountains in that late, open folds are not common in the former. Affinities with the POR schist from other areas are: similar lithology and mineral assemblages, parallelism between fold axes and lineation, and an inverted metamorphic zonation. The Rand Schist is one of the oldest bodies of POR schist; a granodiorite that intruded the schist after metamorphism has a U-Pb zircon age of 79±1 Ma (Silver & Nourse 1986).

Sierra Pelona

In the Sierra Pelona, Graham (1975) and Graham & England (1976) have described an inverted metamorphic zonation from lower greenschist facies away from the VCM fault to oligoclase-amphibolite facies and locally amphibolite facies at the contact with the mylonites and concluded that conductive heating as well as shear heating was needed to account for the inverted metamorphic zonation. Jacobson (1983c) has described isoclinal folds with axial-planar schistosity that are overprinted by more open folds with the same axial trend in the POR schist of this area.

Orocopia Mountains

The POR schist in the Orocopia Mountains exhibits folds overprinted by open folds (Jacobson 1983c, Jacobson & Dawson 1995). Open folds in this area show a wider range of orientations than in other bodies of POR schist, and are assigned to two different generations. Folds and lineations trending NE-SW occur at all structural levels and have formed during an early phase of deformation. Lineations and folds that trend NW-SE are restricted to the proximity of the fault, and are interpreted as exhumation-related structures (Jacobson & Dawson 1995). The latter structures show consistent NE sense of transport of upper plate rocks. In contrast to the Rand and San Gabriel Mountains, mylonitic rocks in the Orocopia Mountains are located at top of the schist sequence whereas upper plate rocks are brittlely deformed. Post-metamorphic reactivation along the Orocopia fault is indicated by retrogression of garnet, biotite, epidote, and calcic amphibole in the Orocopia Schist. Amphibole compositional trends for both lithologic units show a gap in metamorphic conditions, and indicate high-P/low-T metamorphism for the Orocopia Schist and higher temperatures for the upper plate rocks (Jacobson & Dawson 1995).

Gavilan Hills

In the Gavilan Hills area, the POR schist shows a complex structure with two penetrative lineations: NE-SW away from the VCM fault, and ENE-WSW close to the contact. A set of appressed isoclinal folds seems to be the oldest structure preserved in the schist. Late, tight-to-open folds, with or without an axial plane foliation, show a wide range of trends and are locally refolded. A NE direction of movement for upper plate rocks has been inferred along the Chocolate Mountains fault based on the sense of asymmetry of late folds and other shear sense indicators (Haxel 1977, Haxel & Dillon 1978, Simpson 1986, 1990, Dillon et al. 1990). This segment of the VCM fault has been regarded as the original "burial thrust" along which the POR schist was accreted to North America, and the sense of transport has been used to constraint a tectonic model for the origin of the schist.

Lately, interpretation of several segments of the VCM fault as reactivated faults due to Tertiary extensional tectonics, makes determination of the nature of this segment critical in understanding the evolution of the POR schist and its tectonic setting.

Purpose and Scope

In order to determine the relationship between deformation and metamorphism, a detailed survey of structures was conducted on the Orocopia Schist and upper plate rocks in the Gavilan Hills. The areal distribution of microstructures close to and away from the contact was examined using graphical techniques. As a result, evidence of reactivation along the Chocolate Mountains fault was documented. Shear bands and mylonite zones were assigned to two different fault geometries, however, a series of transitional structures was observed. Structures indicating a NE sense of transport for the upper plate rocks were found to be related to retrogression of the fabrics during uplift rather than subduction

Determination of mineral assemblages and their relationship to deformation and metamorphism for both lithologic units was evaluated using petrographic analysis. A group of selected samples was analyzed using the electron microprobe and both qualitative and quantitative thermobarometric determinations were made. Pressure and temperature of metamorphism were assessed for the Orocopia Schist and upper plate rocks. The degree of metamorphic continuity between both structural units was evaluated using the structural, petrographic, and probe data. We concluded that a gap in metamorphic conditions exists between the Orocopia Schist and upper plate rocks in the Gavilan Hills. Finally, a two-stage exhumation of the Orocopia Schist was proposed and the importance of a N-dipping set of normal faults was emphasized.

Dissertation Organization

This dissertation is composed of two papers. The first paper, entitled "The Chocolate Mountains fault in the Gavilan Hills area of southeastern California: Evidence of extensional reactivation and implications for the tectonic setting of the Orocopia Schist" deals mostly with the structural evolution of the area and will be submitted to the *Journal of Structural Geology*. The second paper, entitled "Estimation of metamorphic conditions in rocks of the Chocolate Mountains fault, Gavilan Hills of Southeastern California: Evidence of post-subduction reactivation" is concerned with the evaluation of metamorphic conditions in both the Orocopia Schist and upper plate rocks and will be submitted to the *Journal of Metamorphic Geology*. In order to be consistent, the format and reference style chosen for both papers and all other sections follows that of *Journal of Structural Geology*. Following the second paper is a general summary and a list of references cited in the general introduction.

THE CHOCOLATE MOUNTAINS FAULT IN THE GAVILAN HILLS AREA OF SOUTHEASTERN CALIFORNIA: EVIDENCE OF EXTENSIONAL REACTIVATION AND IMPLICATIONS FOR THE TECTONIC SETTING OF THE OROCOPIA SCHIST

Felix R. Oyarzabal, Carl E. Jacobson and Gordon B. Haxel

A paper to be submitted to *Journal of Structural Geology*

Abstract

The Chocolate Mountains fault in southeastern California has been considered the original structure along which the oceanic Orocopia Schist was underplated beneath plutonic and metamorphic rocks of the continental U.S. A detailed structural analysis in the Gavilan Hills area of southeastern California, however, shows a deformation zone localized at top of the schist with structures similarly oriented to those in the upper plate but different from ones in the structurally deep schist. The deformation zone contains several generations of shear zones and mylonites that originated in a ductile environment and were progressively overprinted by brittle deformation. These structures formed during retrograde metamorphism and record the exhumation rather than the subduction of the Orocopia Schist. The Gatuna fault, previously considered a brittle middle- to late-Tertiary fault, which places the Winterhaven Formation against upper-plate gneisses in the Gavilan Hills, is also part of the exhumation structure. An older origin in a ductile regime is here proposed for this fault. Both structural and geochronological evidence suggest two distinctive episodes of uplift for the Orocopia Schist in the Gavilan Hills. The first stages of uplift occurred in early Tertiary time, when the schist and upper plate were brought to middle crustal levels. Final unroofing took place probably during middle- to late-Tertiary time.

Introduction

The Vincent-Chocolate Mountains (VCM) fault system of southern California and southwesternmost Arizona (Fig. 1) separates a lower plate of oceanic Pelona-Orocopia-Rand (POR) Schist of Late Cretaceous-early Tertiary metamorphic age from an upper plate of

Precambrian to Mesozoic intrusive and metamorphic rocks of continental affinity (Ehlig 1958, 1968, 1981, Haxel & Dillon 1978, Jacobson *et al.* 1988). The various fragments of this system are exposed in post-metamorphic antiforms dispersed along the San Andreas and related faults (Crowell 1981, Ehlig 1981). The VCM fault system has commonly been regarded as the original structure along which the POR schist was subducted beneath the continental basement. This interpretation is based on the convergence of metamorphic temperature at the top of the schist and base of the upper plate in the San Gabriel Mountains and the parallelism of foliation, folds and lineations between the schist and upper plate in several segments of the system (Ehlig 1958, 1968, 1981, Haxel 1977, Haxel & Dillon 1978, Jacobson 1983a, b, Postlethwaite & Jacobson 1987, Dillon *et al.* 1990). Based on various indicators of high-pressure metamorphism, the schist has been considered to be the remnants of a subduction complex.

There are two main models for the origin of the POR schist and VCM fault. Northeast sense of transport of the upper plate in several ranges of southeasternmost California has been considered evidence of accretion of the POR schist along a SW-dipping subduction zone during collision of a microcontinent with North America (Haxel & Dillon 1978, Vedder *et al.* 1983, Haxel & Tosdal 1986, Dillon *et al.* 1990). This model, however, requires a terrane boundary NE of the outcrops of POR schist, but such a boundary has yet to be recognized (Burchfiel & Davis 1981, Crowell 1981, Powell 1981). A different model considers that the POR schist was accreted in an E-dipping, Andean-type subduction zone and is an extension of the Franciscan Complex (Crowell 1968, 1981, Yeats 1968, Burchfiel & Davis 1981, Dickinson 1981, Sharry 1981, Hamilton 1987, 1988, Barth 1988, Jacobson & Dawson 1995, Malin *et al.* 1995). This model requires the NE movement direction to be related to a late phase of deformation (Burchfiel & Davis 1981, Crowell 1981, Hamilton 1987, 1988). Evidence that several segments of the VCM fault have been reactivated as extensional faults during the exhumation of the POR schist is consistent with the Andean-type model (Crowell 1962, Frost & Martin 1983, Haxel *et al.* 1985, Drobeck *et al.* 1986, Postlethwaite & Jacobson 1987, Jacobson *et al.* 1988, Richard & Haxel 1991, Jacobson & Dawson 1995). In particular, structures with NE direction of transport in the Orocopia Mountains formed during the extensional reactivation and have no bearing on the original direction of movement along the VCM fault (Jacobson *et al.* 1988, Jacobson 1990, Jacobson & Dawson 1995).

The area known informally as the Gavilan Hills, located SE of the Chocolate Mountains in southeasternmost California, is particularly important because there the fault has been interpreted as the original "thrust" or subduction zone. Most of the data about NE sense of transport of the upper plate used to support the microcontinent collision model come from the Gavilan Hills and vicinity (Haxel & Dillon 1978, Dillon *et al.* 1990), making this the ideal place to study the relations between the Orocopia Schist and the upper plate and test the validity of the tectonic model. A microstructural study in part of the Gavilan Hills by Simpson (1990) corroborated the NE transport direction for the upper plate rocks but also postulated a late-stage origin for those structures. Our structural analysis covers all the outcrops of Orocopia Schist and upper plate located south of Gavilan Wash, between Indian Pass and Carrizo Wash and is complemented by a petrologic study of upper plate rocks and Orocopia Schist (Oyarzabal & Jacobson, 1996). We try to establish in particular whether the present contact between the Orocopia Schist and upper plate is a relic of the original subduction zone or a reactivated fault with no bearing on the original direction of transport. We argue here that the contact is a normal fault and that structures with NE sense of transport were produced during uplift and do not indicate subduction direction. A two-stage uplift history for the Orocopia Schist in the Gavilan Hills is suggested, with initial movement in early-Tertiary time and final unroofing in middle- to late-Tertiary time.

Geologic Setting

The VCM fault in southeasternmost California is exposed in a series of culminations along the Chocolate Mountains anticlinorium, a structure that extends from the Chocolate Mountains to southwestern Arizona (Fig. 1, Haxel *et al.* 1985). The Gavilan Hills occurs along one of these culminations, in the central part of the anticlinorium. The Orocopia Schist is the structurally lowest tectonostratigraphic unit in the region and crops out in the core of the antiform (Fig. 2). The upper plate constitutes a thin slice above the Chocolate Mountains fault on the northern and eastern flanks of the antiform and forms two klippen in the central part of the area. The Jurassic (?) Winterhaven Formation, a sequence of low-grade metasedimentary and metavolcanic rocks, along with volcanic rocks of middle Tertiary age are also exposed on the northern and eastern flanks of the antiform (Haxel *et al.* 1985). The Winterhaven Formation is in contact with the upper plate and Orocopia Schist along the Gatuna fault, which dips steeply to the north.

Radiometric Ages

Two Rb-Sr mineral-isochron ages from the San Gabriel Mountains (59 ± 1 and 58.5 ± 4 Ma) from schist and mylonite, respectively, have been considered to date the time of metamorphism of the POR schist (Ehlig 1981). Dillon (1986) argued for a somewhat older age for the metamorphism, based on the distribution of K-Ar ages of Miller & Morton (1980) from upper-plate rocks in the San Gabriel Mountains. Biotite K-Ar ages, mostly from igneous rocks, increase gradually from 60 Ma at the base of the upper plate to 74-75 Ma at high structural levels. Dillon (1986) concluded that the age gradient was evidence of erosional unroofing during accretion of the Pelona Schist and that oldest ages indicated the initiation of this event. More recently, Jacobson & Barth (1993) pointed to a more complex cooling history for the San Gabriel Mountains and concluded that the age of metamorphism is indicated by the K-Ar ages at the base of the upper plate (~ 60 Ma), consistent with the Rb-Sr mineral ages and with $^{40}Ar/^{39}Ar$ ages from Pelona Schist in this region (Jacobson 1990).

In the Gavilan Hills, $^{40}Ar/^{39}Ar$ cooling ages from hornblende and muscovite in the schist are 47.7 ± 2.0 Ma and 49.7 ± 0.2 Ma, respectively (Jacobson 1990). Two apatite fission track ages from schist in the Gavilan Hills are 18.7 ± 7 Ma and 19.1 ± 7.6 Ma (Boettcher, personal comm.). U-Pb zircon ages of 163.2 Ma and 160.9 Ma from a pre-metamorphic dioritic dike in the Chocolate Mountains are interpreted as the minimum age for the Orocopia Schist protolith (Mukasa *et al.* 1984).

The only radiometric constraint on the age of the upper plate in the Gavilan Hills is an apatite fission-track age of 18.3 ± 2.2 Ma (Boettcher, personal comm.), but these rocks are probably derived from Triassic and or Jurassic plutonic rocks. Hornblende $^{40}Ar/^{39}Ar$ cooling ages from similar rocks in the Cargo Muchacho Mountains, approximately 20 km to the south, range from 60 to 63 Ma whereas K-Ar ages of biotite vary from 53 Ma at the deepest structural levels to 62 Ma at high structural level (Tosdal *et al.* 1993). Biotite and feldspar from the upper plate in the Chocolate Mountains give ages of about 38 Ma (Manske *et al.* 1988).

Rock Types and Mineral Assemblages

Orocopia Schist

The Orocopia Schist is composed principally of metagraywacke (at least 95%) with subordinate metabasalt, metachert and marble. A serpentinite body, composed of antigorite and accessory magnetite, is exposed in the central part of the area (Haxel 1977). The prograde assemblage in the metagraywacke consists mainly of quartz, biotite, muscovite and oligoclase. Oligoclase forms poikiloblasts up to 5 mm in diameter, with quartz, biotite, muscovite, epidote, titanite and graphite as inclusions. Additional components are garnet, epidote, K-feldspar, opaques, titanite, rutile, graphite, zircon and apatite. Retrogression of the metagraywacke is widespread, as indicated by the common replacement of biotite and garnet by chlorite (Fig. 3 a), oligoclase margins by albite and oligoclase by calcite.

The metabasalt is composed principally of hornblende, oligoclase and epidote. Additional minerals are garnet, biotite, titanite, rutile, and magnetite. As in the metagraywacke, oligoclase poikiloblasts are common, with inclusion trails of one or several of the minerals quartz, hornblende, garnet, biotite, titanite and epidote. Evidence of retrogression is extensive and includes (1) rims of actinolite on hornblende and albite on oligoclase, (2) chloritization of hornblende, epidote and rare matrix garnet, (3) saussuritization of plagioclase and (4) the fact that garnet is common as inclusion in plagioclase, despite being rare in the matrix.

The prograde assemblage of oligoclase + epidote + hornblende indicates that the Orocopia Schist belongs to the lower amphibolite facies (facies definition of Graham and Powell 1984). Garnet-hornblende and qualitative amphibole thermometry of mafic schist from the Gavilan Hills (Oyarzabal & Jacobson 1996) indicates prograde temperatures between those of the albite-epidote- and oligoclase-amphibolite facies, similar to metamorphic conditions for lower amphibolites from the Rand Mountains (Jacobson 1995). Occurrence of biotite in the matrix of the metagraywacke and amphibolite is a characteristic of the schist in the Gavilan Hills, suggesting probably a higher temperature of metamorphism than in other exposures of the schist or a lower Al-bulk compositions. Chorite is also present in the matrix of the metagraywacke and mafic schist of the Gavilan Hills but textural evidence indicates that it formed at a late stage of deformation during retrogression. The occurrence of garnet as inclusions in feldspar but not in the matrix of the mafic schist has previously been described in the Orocopia Mountains (Jacobson & Dawson 1995) is evidence of a pervasive retrogressive overprint.

Upper Plate

Principal rock types in the upper plate of the Chocolate Mountains fault in the Gavilan Hills are tonalitic to granitic gneiss, amphibolitic gneiss and amphibolite. The tonalitic to granitic gneiss is composed of quartz, plagioclase, K-feldspar, biotite, epidote and muscovite.

with tonalitic compositions more abundant than granitic ones. Minor titanite, apatite, zircon and rutile are present in most samples and garnet and hornblende are present locally. The amphibolite is composed of approximately equal parts of hornblende and plagioclase, with minor epidote, biotite, quartz, titanite and opaques. The above mineral assemblages indicate peak-metamorphic conditions in the middle amphibolite facies. However, there is pervasive retrogression to the greenschist facies as indicated by sericitization and saussuritization of plagioclase (Fig. 3 b), chloritization of garnet, hornblende, and biotite and riming of hornblende by actinolite.

Structure

Orocopia Schist

A structural thickness of about 400 m of Orocopia Schist crops out in the Gavilan Hills. The main fabric in the schist is a well developed foliation (Fig 4 & 5), axial planar to highly appressed isoclinal folds. In general, foliation has shallow to intermediate dip (mostly 10° to 30°, Fig. 4 & 6 subareas *F* to *O*) with steeper dips occurring along the northern flank of the antiform (Fig. 5, compare subareas *H, I* & *K* with subareas *M, N* & *O*). Folded inclusion trails of graphite in oligoclase porphyroblasts and relict muscovite grains oriented at a high angle to the main foliation are evidence of multiple phases of transposition of foliation as previously inferred for the Pelona Schist in the San Gabriel Mountains (Jacobson 1983c). The foliation describes a broad domal-structure elongated almost E-W. The dome has more than a single hinge as indicated by the local distribution of foliation (Figs. 4 & 6 subareas *F* to *O*).

Two distinctive penetrative lineations are associated with the foliation (Fig. 4, 5 & 6 *F* to *O*). The older one (L1) trends NNE and is present at all structural levels in most of the area. A younger lineation (L2), trends ENE to EW and is restricted to a narrow area adjacent to the Chocolate Mountains fault on the northern and eastern flanks of the antiform (Fig. 5 & 6 subareas *F* & *I*) and to shear zones in the schist. This lineation is better exposed in subareas

G and *H* of Fig. 6, where it parallels the trace of the contact between the Orocopia Schist and upper plate and it also parallels a series of E-W striking shear zones. Locally, the different trends may be due to rotation of foliation near the Chocolate Mountains fault. For example, in the region depicted in Fig. 7, lineation with NNE-trend occurs where foliation dips NNW, whereas ENE-trending lineation are associated with N- to NNE-dipping foliation. However, this mechanism alone can not account for the abrupt shift in orientation of the lineation close to the Chocolate Mountains fault in the central part of the area (Fig. 6 subareas *G* and *H*). Both lineations are defined by intersection of foliation and compositional layering, intersection of foliation planes and crenulation cleavage, and preferred orientation of mineral grains but L1 is more pervasive than L2. The lineation in the Pelona and Rand Schists is parallel to the direction of greatest elongation (Jacobson 1983b, Postlethwaite & Jacobson 1987). In the Gavilan Hills, the older lineation appears associated with the prograde assemblage and, by analogy to the Rand and Pelona Schist, is considered to be a stretching lineation. The second lineation is younger and seems to be related to extensional reactivation of the Chocolate Mountains fault. The relation of lineations to fold axes is complex. In some places the lineation is parallel to the axes of open folds, as in the case of most of the crenulation lineations, whereas in others it is oriented at a low angle to them.

The schist contains a variety of shear zones, which we divide into two end-members for ease of description. Type I shear zones, which are the older of the two, occur throughout the schist , but are most abundant in the upper 100 m of the section. They are a centimeter to a meter thick and their boundaries are generally parallel to the foliation of the surrounding schist. There are at least two foliation in type I shear zones. The oldest one is similar to that present throughout the schist and is parallel to slightly oblique to the boundaries of the shear zone. The second foliation is characterized by shear bands (cf. Simpson & Schmid 1983, Lister & Snoke 1984) that are inclined to the boundaries of the shear zones. The geometry of the shear bands indicate top-to-the-ENE to top-of-the-E sense of transport. In thin section, relatively coarse micas, quartz and feldspar that define the old foliation are cut by thin shear bands showing grain-size reduction. Quartz and feldspar in both the coarse and fine areas are relatively equidimensional and strain free. However, widespread replacement of biotite and garnet by chlorite indicates that the type I shear zones are retrogressive in origin. The chlorite occurs both as individual matrix grains and as aggregates of grains along the shear bands. Early chlorite grains are folded by the crenulation, other grains occur as "saddle reefs" in crenulation hinges or are axial planar to the crenulation.

Type II shear bands are present only in the top 100 m of the sequence and are characterized by protomylonitic to ultramylonitic textures as opposed to crystalloblastic ones (Fig. 8a). They range in thickness from a centimeter to about five meters and are oriented at a moderate to high angle to the foliation of the schist. At least two foliations are also present in type II shear zones. The oldest one is characterized by mica fish and elongated aggregates of quartz and feldspar showing mylonitic textures (Fig 8b). This old foliation is cut by shear bands with evidence of grain size reduction. Microstructural indicators and the relative orientations of foliations indicate top-to-the-ENE to top-to-the-E sense of transport. Type II shear zones are generally overprinted by an array of fractures and cataclastic zones and quartz-rich veins stained with iron oxide are frequent. The main differences between type I and type II shear zones lie in their relation to the schist foliation and in the mylonitic character of the latter.

Upper plate

The upper plate represents part of a continental magmatic arc association, with a complex polymetamorphic and deformational history. The upper plate in the Gavilan Hills, although less than 120 m thick, has a complex structure that records at least two phases of deformation. The oldest discernible structure is a gneissic foliation similar to that in gneisses throughout the upper plate of the VCM fault in the eastern and central Transverse Ranges and adjacent areas (Ehlig 1981, Crowell 1981, Powel 1981, Jacobson 1983a, 1996, Jacobson

& Dawson 1995). The foliation closely follows the schist in defining the broad antiform (Fig. 4, 5 & 6 subareas *A* to *D*), and however old, it has been enhanced due to deformation along the present contact with the Orocopia Schist, as indicated by sericitized and saussuritized plagioclase grains and undulatory quartz grains flattened along the foliation plane. The lineation trends mostly ENE to EW (Fig. 4 & 6 *A* to *D*) and is better developed in retrograded gneisses and amphibolites. The lineation has developed at a younger stage of deformation and parallels the orientation of the lineation in the schist along the present contact. An older lineation with a WNW trend, probably related to the prograde metamorphism of the upper-plate gneisses, is common in subarea *B* of Fig. 6 and is sporadically present throughout the upper plate. The parallelism of lineation between the schist and upper plate along the contact clearly indicates the common deformational history of both structural units during retrogression of the mineral assemblages.

Shear zones, ranging from 20 cm to a few meters thick, cross cut the foliation of the gneiss at a moderate to high angle and generally are associated with mylonites (Fig. 9a). They are similar to the type II shear zones in the schist but show a more pervasive cataclastic overprint by fractures and veins with quartz and iron oxides (Fig. 9b). The cataclastic overprint increases toward the top of the sequence. Sericitization and saussuritization of broken porphyroclasts of feldspars and mortar texture in quartz are common in the matrix, and are associated with chloritization of biotite and amphibole indicating that the shear zone deformation occurred during retrogression.

The Chocolate Mountains fault

The Chocolate Mountains fault is a complex structure that includes at least two different fault geometries. In the central part of the antiformal structure there are two klippen of upper-plate rocks in contact with the schist along a low-angle fault (Fig. 2). A similar low-angle fault exposes the upper plate in the SE part of the area. These low-angle faults are associated with type I shear zones. The present Chocolate Mountains fault along the northern flank of the antiform is composed of moderate to gentle, N- or NE-dipping faults alternating with steep, N-dipping segments, all of which are characterized by mylonitic rocks and shear zones. The contact has been later segmented by high-angle N- and NW-striking faults. Locally (subarea *B* in Fig. 5) a steep N-dipping mylonite that constitutes the contact between the schist and upper plate extends into a mylonite zone with similar orientation and texture that lies entirely within the upper plate, confirming a complex reactivation pattern along the Chocolate Mountains fault.

An increase of fractures and cataclastic textures occurs toward the top of the upper plate sequence, culminating in a cataclastic zone up to 5 m thick, along the Gatuna fault. The Gatuna fault has been considered a brittle, middle-Tertiary structure by Haxel et al. (1985), but a closer look reveals that this zone of deformation has originated under a ductile regime. Locally, protomylonitic, mylonitic and ultramylonitic rocks occur along the fault. These rocks are overprinted by fractures, veins and cataclastic zones with recrystallization of quartz and precipitation of calcite and oxides in a fluid rich environment under greenschist facies conditions, as indicated by recrystallization of green, low-Ti biotites. A penetrative ENE-trending lineation is common in these rocks and correlates with the lineation present along the contact between the schist and the upper plate. The mylonitic origin of the rocks located along the Gatuna Fault suggests that this structure originated in early-Tertiary time and probably has been subsequently reactivated. The similarities between the shear zones in the schist and upper plate, the progressive increase of brittle overprint from the base of the upper plate toward the top of the section, the presence of an ENE lineation in the gneisses, and the ductile origin of the Gatuna fault indicate a genetic relationship between these structures and the Chocolate Mountains fault.

Folds and transport direction

The oldest folds in the Orocopia Schist are highly appressed isoclinal folds with well developed axial-planar schistosity. They have been referred to as intrafolial folds by Haxel

(1977), Haxel & Dillon (1978) and Dillon *et al.* (1990) and are equivalent to the style 1 folds of Jacobson (1983c) in the Pelona Schist. The isoclinal folds tend to weather along the axial-planar schistosity rather than along the folded compositional layers, which makes it difficult to determine their orientations. Based on a few measurements, these folds seem to trend NNE-SSW.

Superimposed on these folds are open-to-tight folds with locally developed axial-planar schistosity. This schistosity is defined by micas and clots of chlorite that have formed by replacement of garnet. Refolded open-to-tight folds and sheath folds were observed locally. Late folds show a wide range of trends (Fig. 4 & 10 subareas *F* to *N*) with most axes trending from N to ENE and from WSW to WNW. There are at least three different fold sets, oriented roughly NE-SW, E-W, and NW-SE. The NE-SW set shows the widest spread in orientations (Figs. 10 subareas *F*, *G*, & *J* to *N* & and 11 *B* & *C*). The second most abundant set of fold axes is the one oriented approximately E-W, (Figs. 10 subareas *F*, *G*, *H*, *J* & *L* and 11 A). Although this set is present at all structural levels, it is particularly distinctive in the NW part of the area. Finally, a NW-SE set is only locally important and is better developed close to the Chocolate Mountains fault (Fig. 11 B & C).

Fold axes in the upper plate show also a wide range of orientation (Fig. 4 & 10 subareas *A* to *D*) but their relative ages are more difficult to assess due to the complex deformational history of these rocks. Folds with mostly ENE to ESE trend and a few with a NNW trend predominate in the upper plate located in the SE side of area (Fig 10 subarea *E*). A similar set of folds, but trending mostly from WSW to WNW is common along the northern flank of the area, with a few folds trending NW (Fig. 10 subareas *A* to *C*). Finally, two set of folds are present in the klippen, the first trending from W to WSW and the second trending NNE (Fig 10 subarea *D*). Unfolding the antiform will combine all these folds in three sets, one trending roughly E-W, a second trending NW-SE and a third trending approximately NNE-SSW.

Haxel & Dillon (1978) and Dillon *et al.* (1990) argued that all the late folds were part of a single set and used the separation-angle method of Hansen (1967, 1971) to infer NE transport of the upper plate along several segments of the Chocolate Mountains fault. Although in fact fold asymmetry indicates NE sense of transport in the Gavilan Hills (Fig. 12), we find that tight clustering or local bimodal distribution of fold axes argue for the presence of several discrete sets of folds, invalidating the Hansen approach to deduce the direction of tectonic transport. Furthermore, the NE trending folds are mostly restricted to the schist (Fig. 4) suggesting that there is no relationship between folds in the upper and lower plates of the Chocolate Mountains fault.

Discussion

Haxel & Dillon (1978), Tosdal *et al.* (1986) and Dillon *et al.* (1990) concluded that the Chocolate Mountains fault was a burial or subduction fault (thrust). That conclusion was based on the approximate parallelism of lineation and foliation and the inferred convergence of metamorphic conditions between schist and upper plate in the southern Chocolate Mountains, Gavilan Hills and adjacent areas. An analogy was drawn to the Vincent thrust in the San Gabriel Mountains (Ehlig 1958, 1981, Jacobson 1983a, b) which exhibits a clear structural and metamorphic convergence between schist and upper plate and which is thought to be a preserved fragment of the original subduction zone (Jacobson 1983a, b, 1996). However, we have found the structural relations in the Gavilan Hills to be considerably more complicated than described by Haxel & Dillon (1978) and Dillon *et al.* (1990) and, in fact, substantially different from those in the San Gabriel Mountains.

Particularly significant is the presence of a zone of deformation at the top of the schist with structures similarly oriented to those in the upper plate but oblique to the ones in the structurally deep schist. The zone of deformation is associated with several generations of shear zones and mylonites that developed during retrogression of mineral fabrics and confirm the suggestion of Simpson (1990) that mylonitization occurred during waning temperatures.

Furthermore, this deformational event seems to be coeval with development of shear zones and mylonites in the upper plate. Overprinting of pre-existing fabrics was pervasive and is recorded in the ENE to EW trending lineations that are common to both the structurally high Orocopia Schist and the upper-plate rocks. Low-angle faults and type I shear zones, which exhibit polygonal textures, presumably record the initiation of uplift in a ductile environment, probably right after subduction at post-peak metamorphic conditions according to determinations of prograde temperature and pressure of metamorphism in the schist (Oyarzabal & Jacobson, 1996). As deformation progressed, Type II shear zones formed with their associated mylonites, indicating progressive cooling with grain size reduction due to exhumation. We suspect that extension was first accommodated by shallow-dipping shear zones and as deformation progressed steep, N-dipping faults became important. At least some of the late open-folds formed during the initial stages of uplift and their asymmetry indicates the direction of extension rather than overthrusting of the upper plate, similarly to the asymmetry of foliations in the shear zones. The onset of extension is indicated by the early Tertiary cooling ages of the Orocopia Schist and upper plate already mentioned. The presence of mylonitic rocks along the Gatuna fault indicate a ductile origin for this structure, but these rocks were pervasively overprinted by brittle fabrics as deformation proceeded. The increasing overprinting of ductile by brittle deformation toward the top of the upper plate suggests that during the final stages of uplift the deformation was transferred to the Gatuna fault and, following that, the Orocopia Schist and upper plate behaved as a coherent unit. The predominant ductile character of most of the extensionally related structures suggests that the first stage of uplift emplaced the Orocopia Schist at upper-middle crustal levels where it cooled to below the closure temperature for Ar diffusion in biotite and was above the brittle-ductile transition zone as indicated by the cataclastic deformation associated with the extensional structures. These structures were brittlely reactivated several times or were truncated by younger N- and NW-striking faults during middle- to late-Tertiary time

(Richard and Haxel 1991).

We propose that final unroofing of the schist occurred during middle- to late-Tertiary time based on apatite fission track data cited previously. Extensional deformation of middle-Tertiary age has been proposed by Frost *et al.* (1982) for regions close to the Gavilan Hills. They suggested uplift of the Orocopia Schist at about 20 Ma based on K-Ar whole-rock ages and regional evidence of detachment faulting at about that time. Sherrod & Tosdal (1991) suggested that unroofing of the schist was younger than the ignimbrite of Ferguson Wash (26 Ma), but may have begun by the time of deposition of the tuff of Felipe Pass (22 Ma) based on the fact that the latter does not extend south of the outcrops of the Chocolate Mountains anticlinorium whereas the former crops out around them. The lack of mylonites of middle-Tertiary age and the moderate dip of normal faults in the area have been cited as evidence that this extensional event was modest and did not expose deep levels to the surface, although it was important enough to unroof the schist and the upper plate. The amount of extension in the Picacho area does not exceed 40% and is considerably less than that in the Gavilan Hills (Sherrod & Tosdal 1991).

The arching of the antiform was produced at this stage, as was probably most of the brittle fracturing and jointing of the area. Multiple episodes of faulting and extension have been proposed by Haxel *et al.* (1988), Richard & Haxel (1991), Sherrod & Tosdal (1991), and Oyarzabal *et al.* (1995) to explain the uplift of the Orocopia Schist. The possibility that most of the E-W striking faults merge at depth into a deeper detachment fault of regional extent has been proposed by Garner *et al.* (1982) and Frost *et al.* (1982), but Sherrod & Tosdal (1991) concluded that middle Tertiary extension was achieved by block tilting of narrow horst and graben structures along moderate dipping normal faults.

Both structural and geochronologic evidence suggest two distinct episodes of uplift of the Orocopia Schist in the Gavilan Hills. The first stage is thought to have occurred during early Tertiary, as registered by cooling ages ranging from 38 Ma to 65 Ma. During this episode of extension, the schist and upper plate were brought to middle crustal levels probably as a response to underplating and tectonic thickening of the Orocopia Schist in a manner similar to Platt's (1986) tectonic model or by a set of anastomosing normal faults as proposed by Jayko *et al.* (1987) for the Coast Range Ophiolite. Extension took place during or right after subduction and was accommodated first by low-angle type I shear zones .and subsequently. by the more steep-dipping type II shear zones. The schist and upper plate remained at mid crustal levels until middle to late Tertiary time as suggested by apatite fission track data and the first appearance of POR schist clast in the sedimentary record (Dillon 1976. Goodman & Malin 1992). The Gatuna fault seems to have been active mainly during the early Tertiary phase of extension, and the preservation of the mylonite along this fault argue against significant middle to late Tertiary reactivation. At present, the structure responsible for the final unroofing of the Pelona Schist and upper plate in the Gavilan Hills has yet to be recognized.

Confirmation of extensional reactivation along the Chocolate Mountains fault and the late origin for the NE vergent structures in the Gavilan Hills remove the necessity for a collisional model to explain the origin of the Orocopia Schist. The POR schist has been considered a lateral equivalent of the Franciscan Complex on grounds of lithologic similarities (Yeats 1968. Crowell 1968. 1981). Those similarities are very significant and lead us to conclude that an Andean-type margin is the most probable tectonic setting for the origin of the POR schist

Our preferred model for the exhumation of the Orocopia Schist is depicted schematically in Fig. 13. We propose that exhumation was originally driven by continuous underplating of schist and gravitational collapse of the upper plate. Although the density of the Orocopia Schist (average of 2.71 g/cm^3 for the metagraywacke and 3.03 g/cm^3 for the mafic schist. Haxel personal communication) is not significantly different from presently contiguous upper plate. the presence of a thick sequence of schist at the base of the crust was buoyant enough to initiate the exhumation process (Fig. 13a). The first stages of uplift involved reactivation of the contact between the schist and upper plate, with development of normal faults at higher structural levels, which merge at depth with the reactivated fault (Fig. 13b). At a later stage the normal faults will cut through the schist, as erosion takes place, to compensate for the isostatic rebound of the crust. The original contact between the upper plate and the schist is fragmented and in some places replaced by moderate to high angle normal faults (Fig. 13c) becoming a composite structure which involve several generations of reactivated faults and shear zones with newly developed normal faults. Brittle structures will overprint ductile ones as the faults bring deeper material above the brittle-ductile transition zone. The first stages of uplift occurred during early-Tertiary times, according to radiometric dating. A small scale cartoon shows the structural relations of the area after final unroofing during middle- to late-Tertiary extension (Fig. 13d) with the location of the present Chocolate Mountains and Gatuna faults.

Acknowledgments

We have benefited from discussions with Andrew Barth, John Crowell, Perry Ehlig, Eric Frost, Warren Hamilton, Daniel May, Stephen Richard, and Richard Tosdal. Field work was supported by National Science Foundation grants EAR-9004354 and EAR-9316916 to Carl Jacobson.

References

Barth, A. P. 1988. Non-exotic terrane model for the Mesozoic San Gabriel terrane, southeasternmost California. *Abs. with Progr. geol. Soc. Am.* **20**, A275.

Burchfiel, B. C. & Davis, G. A. 1981. Mojave Desert and environs. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 217-252.

Crowell, J. C. 1962. Displacement along the San Andreas fault. *Spec. Pap. geol. Soc. Am.* **71**.

Crowell, J. C. 1968. Movement histories of faults in the Transverse Ranges and speculations on the tectonic history of California. *Stanford Univ. publ. geological Sciences* **11**, 323-341.

Crowell, J. 1981. An outline of the tectonic history of southeastern California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.). Prentice-Hall. Englewood Cliffs, New Jersey, 583-600.

Dickinson, W. R. 1981. Plate tectonics and the continental margin of California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.). Prentice-Hall. Englewood Cliffs, New Jersey, 1-28.

Dillon, J. T. 1986. Timing of thrusting and metamorphism along the Vincent-Chocolate Mountains thrust system, southern California. *Abs. with Progr. geol. Soc. Am.* **18**, 101.

Dillon, J. T., Haxel, G. B. & Tosdal, R. M. 1990. Structural evidence for northeastward movement on the Chocolate Mountains thrust, southeasternmost California. *J. geophys. Res.* **95**, 19,953-19,971.

Drobeck, P. A., Hillemeyer, F. L., Frost, E. G. & Liebler, G. S. 1986. The Picacho Mine: A gold mineralized detachment in southeastern California. *Ariz. geol. Soc. Dig.* **XVI**, 187-221.

Ehlig, P. 1958. Geology of the Mount Baldy region of the San Gabriel Mountains, California. Unpublished Ph. D. thesis, University of California, Los Angeles, California.

Ehlig, P. 1968. Causes and distribution of Pelona, Rand, and Orocopia Schist along the San Andreas and Garlock faults. *Stanford Univ. Publ. geol. Sci.* **11**, 294-305.

Ehlig, P. 1981. Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 253-283.

Frost, E. G. & Martin, D. L. 1983. Overprint of Tertiary detachment deformation on the Mesozoic Orocopia Schist and Chocolate Mtns. thrust. *Abs. with Progr. geol. Soc. Am.* **15**, 557.

Frost, E. G., Martin, D. L. & Krummenacher, D. 1982. Mid-Tertiary detachment faulting in southwestern Arizona and southeastern California and its overprint on the Vincent thrust system. *Abs. with Progr. geol. Soc. Am.* **14**, 164.

Garner, W. E., Frost, E. G., Tanges, S. E. & Germinario, M. P. 1982. Mid-Tertiary detachment faulting and mineralization in the Trigo Mountains, Yuma County, Arizona. In: *Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada* (edited by Frost, E. G. & Martin, D. L.), Cordilleran Publishers, San Diego, California, 159-171.

Graham, C. M. & Powell, R. 1984. A garnet-hornblende geothermometer: calibration, testing, and application to the Pelona Schist, Southern California. *J. metamorph. Geol.* **2**, 13-31.

Hamilton, W. 1987. Crustal extension in the Basin and Range Province, southwestern United States. In: *Continental Extensional Tectonics* (edited by Coward, M. P., Dewey, J. F., & Hancock, P. L.), *Spec. Publs. geol. Soc. Lond.* **28**, 155-176.

Hamilton, W. 1988. Tectonic setting and variations with depth of some Cretaceous and Cenozoic structural and magmatic systems of the western United States. In: *Metamorphism and Crustal Evolution of the Western United States* (edited by Ernst, W. G), Prentice-Hall, Englewood Cliffs, New Jersey, 1-40.

Hansen, E. 1967. Method of deducing slip-line orientations from geometry of folds. *Carnegie Institution of Washington Year Book* **65**, 387-405.

Hansen, E. 1971. *Strain Facies*. Springer-Verlag, New York.

Haxel, G. B. 1977. The Orocopia Schist and the Chocolate Mountain Thrust, Picacho-Peter Kane mountain area, southeasternmost California. Unpublished Ph.D. thesis. University of California, Santa Barbara, California.

Haxel, G .B. & Dillon, J. T. 1978. The Pelona-Orocopia Schist and Vincent-Chocolate Mountains Thrust System, Southern California. In: *Mesozoic Paleogeography of the Western United States* (edited by Howell, D. J. & McDougall, K. A.), Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium **2**, 453-469.

Haxel, G. B., Jacobson, C. E. & Tosdal, R. M. 1988. Multiple low-angle faults atop the Orocopia Schist, southwestern Arizona and southeastern California. *Abs. with Progr. geol. Soc. Am.* **20**, A383.

Haxel, G. B. & Tosdal, R. M. 1986. Significance of the Orocopia Schist and Chocolate Mountains thrust in the late Mesozoic tectonic evolution of the southeastern California-southwestern Arizona region: extended abstract. In: *Frontiers in Geology and Ore Deposits of Arizona and the Southwest* (edited by Beatty, B. & Wilkinson, P. A. K.), *Ariz. geol. Soc. Dig.* **16**, 282-293.

Haxel, G. B., Tosdal, R. M. & Dillon, J. T. 1985. Tectonic Setting and lithology of the Winterhaven Formation: A new Mesozoic stratigraphic unit in southeasternmost California and southwestern Arizona. *Bull. U.S. geol Surv* **1599**, 1-19.

Haxel, G. B., Tosdal, R. M. & Dillon, J. T. 1986. Field guide to the Chocolate Mountains thrust and Orocopia Schist, Gavilan Wash area, southeasternmost California. In: *Frontiers in Geology and Ore Deposits of Arizona and the Southwest* (edited by Beatty, B. & Wilkinson, P. A. K.), *Ariz. geol. Soc. Dig.* **16**, 52-61.

Jacobson, C. E. 1983a. Relationship of deformation and metamorphism of the Pelona Schist to movement on the Vincent Thrust, San Gabriel Mountains, southern California. *Am. J. Sci.* **283**, 587-604.

Jacobson, C. E. 1983b. Structural geology of the Pelona Schist and Vincent thrust. San Gabriel Mountains, California. *Bull. geol. Soc Am.* **94**, 753-767.

Jacobson, C. E. 1983c. Complex refolding history of the Pelona, Orocopia, and Rand Schists. southern California. *Geology* **11**, 583-586.

Jacobson, C. E. 1990. The 40Ar/39Ar geochronology of the Pelona Schist and related rocks. southern California. *J. geophys. Res.* **95**, 509-528.

Jacobson, C. E. 1997. Metamorphic convergence of upper and lower plates of the Vincent thrust, San Gabriel Mountains, southern California. *J. metamorph. Geol.* (in review).

Jacobson, C. E. & Barth, A. P. 1993. A reevaluation of the age of the Vincent-Chocolate Mountains thrust system, southern California. *Abs. with Progr. geol. Soc. Am.* **25**, 56.

Jacobson, C. E. & Dawson, M. R. 1995. Structural and metamorphic evolution of the Orocopia Schist and related rocks, southern California: Evidence for late movement on the Orocopia Fault. *Tectonics* **14**, 933-944.

Jacobson, C. E., Dawson, M. R. & Postlethwaite, C. C. 1988. Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California. In: *Metamorphism and Crustal Evolution of the Western United States* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 976-997.

Jayko, A. S., Blake, M. C., Jr. & Harms, T. 1987. Attenuation of the Coast Range Ophiolite by extensional faulting, and nature of the Coast Range "thrust." California. *Tectonics* **4**, 475-488.

Malin, P. E., Goodman, E. D., Henyey, T. L., Li, Y. G., Okaya, D. A., & Saleeby, J. B. 1995. Significance of seismic reflections beneath a tilted exposure of deep continental crust. Tehachapi Mountains, California. *J. geophys. Res.* **10**, 2069-2087.

Manske, S. L., Matlack, W. F., Springett, M. W., Strakele, A. E.. Jr., Watowich. S. N., Yeomans, B., & Yeomans, E. 1988. Geology of the Mesquite deposit. Imperial County. California. *Min. Eng.* **40**, 439-444.

Miller, F. K. & Morton, D. M. 1980. Potassium-argon geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California. *Prof. Pap. U.S. geol. Surv.* **1152**, 1-30.

Mukasa, S. B., Dillon, J. T. & Tosdal, R. M. 1984. A Late Jurassic minimum age for the Pelona-Orocopia Schist protolith, southern California. *Abs. with Progr. geol. Soc. Am.* **16**. 323.

Oyarzabal, F. R., Jacobson, C. E. & Haxel, G. B. 1995. The Chocolate Mountains Fault in the Gavilan Hills of southeasternmost California: an exhumation related normal fault. *Abs. with Progr. geol. Soc. Am.* **27**, A286.

Oyarzabal, F. R. & Jacobson, C. E. 1997. Estimation of metamorphic conditions across the Chocolate Mountains Fault in the Gavilan Hills of southeastern California: Evidence of post-subduction reactivation. Submitted to *J. metamorph. Geol.*

Platt, J. P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Bull. geol. Soc. Am.* **97**, 1037-1053.

Postlethwaite, Clay C., & Jacobson, Carl E., 1987. Early history and reactivation of the Rand Thrust, southern California. *J. Struct. Geol.* **9**, 195-205.

Powell, R. 1981. Geology of the crystalline basement complex, eastern Traverse Ranges, southern California: Constraints on regional tectonics interpretations. Unpublished Ph.D. Thesis. California Institute of Technology, Pasadena, California.

Richard, S. M. & Haxel, G. B. 1991. Progressive exhumation of the Orocopia and Pelona Schist along a composite normal fault system, southeastern California and southwestern Arizona. *Abs. with Progr. geol. Soc. Am.* **23**, 92.

Sharry, J. 1981. The Geology of the western Tehachapi Mountains, California. Unpublished Ph.D. thesis. Massachusetts Institute of Technology, Massachusetts.

Sherrod, D. R. & Tosdal, R. M. 1991. Geologic setting and tertiary structural evolution of southwestern Arizona and southeastern California. *J. geophys. Res.* **96**, 12,407-12,423.

Simpson, C. 1990. Microstructural evidence for northeastward movement on the Chocolate Mountain fault zone, southeastern California. *J. geophys. Res.* **95**, 529-537.

Simpson, C. & Schmid, S. M. 1983. An evaluation of criteria to determine the sense of movement in sheared rocks. *Bull. geol. Soc. Amer.* **94**, 1281-1288.

Tosdal, R. M., Conrad, J. E. & Murphy, G. P. 1993. Latest Cretaceous and Paleocene extension in SE California. *Abs. with Progr. geol. Soc. Am.* **25**, 155.

Tosdal. R. M., Haxel, G. B. & Dillon, J. T. 1986. Evidence for and tectonic implications of northeastward movement on the Chocolate Mountains thrust, SE California. *Abs. with Progr. geol. Soc. Am.* **18**, 193.

Vedder, J. G., Howell, D. G. & McLean, H. 1983. Stratigraphy, sedimentation, and tectonic accretion of exotic terranes, southern Coast Ranges, California. In: *Studies in Continental Margin Geology* (edited by Watkins, J. S. & Drake, C. L.), *Mem. Am. Ass. Petrol. Geol.* **34**, 471-496.

Yeats, R. S., 1968. Southern California structure, seafloor spreading, and history of the Pacific Basin. *Bull. geol. Soc. Am.* **79**, 1693-1702.

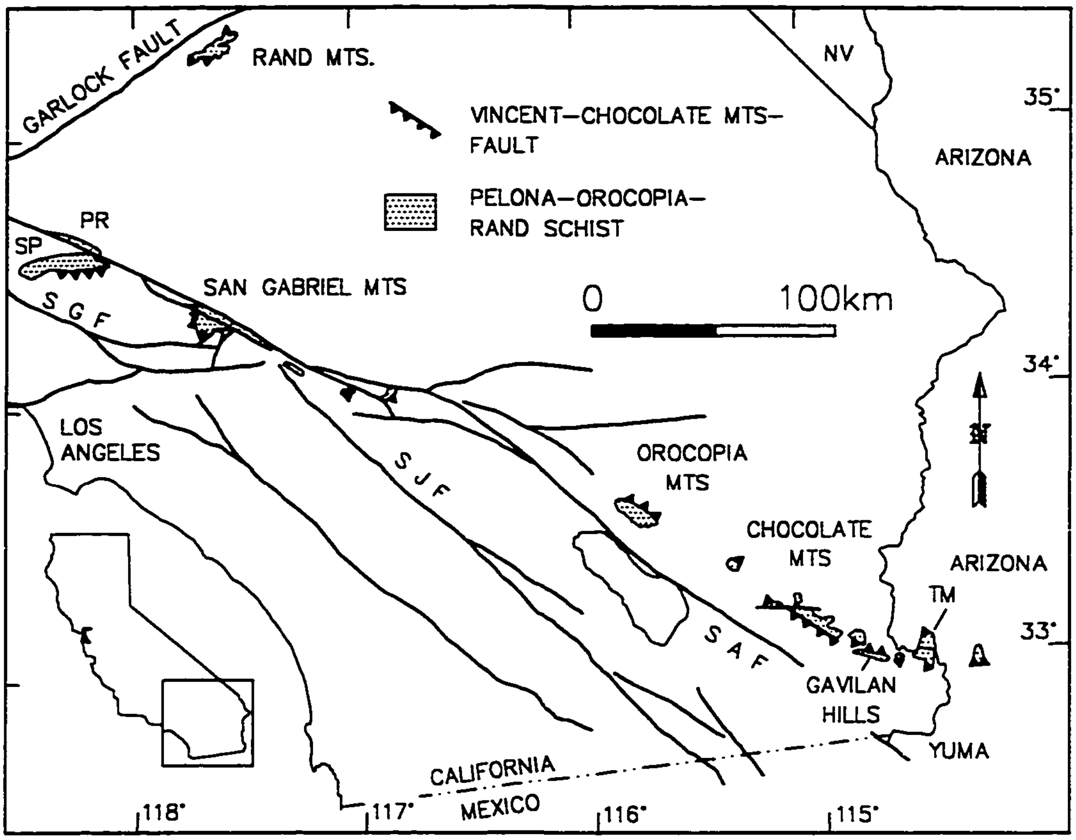

Figure 1. Distribution of the Pelona-Orocopia-Rand Schist and Vincent-Orocopia-Chocolate Mountains fault in southern California. Additional occurrences of the schist are located to the northwest and southeast. The figure follows convention by using barbs to ornament the faults. However, many of the structures have probably been reactivated as normal faults. PR, Portal Ridge; SP, Sierra Pelona; SAF, San Andreas fault; SGF, San Gabriel fault; SJF, San Jacinto fault; TM, Trigo Mountains.

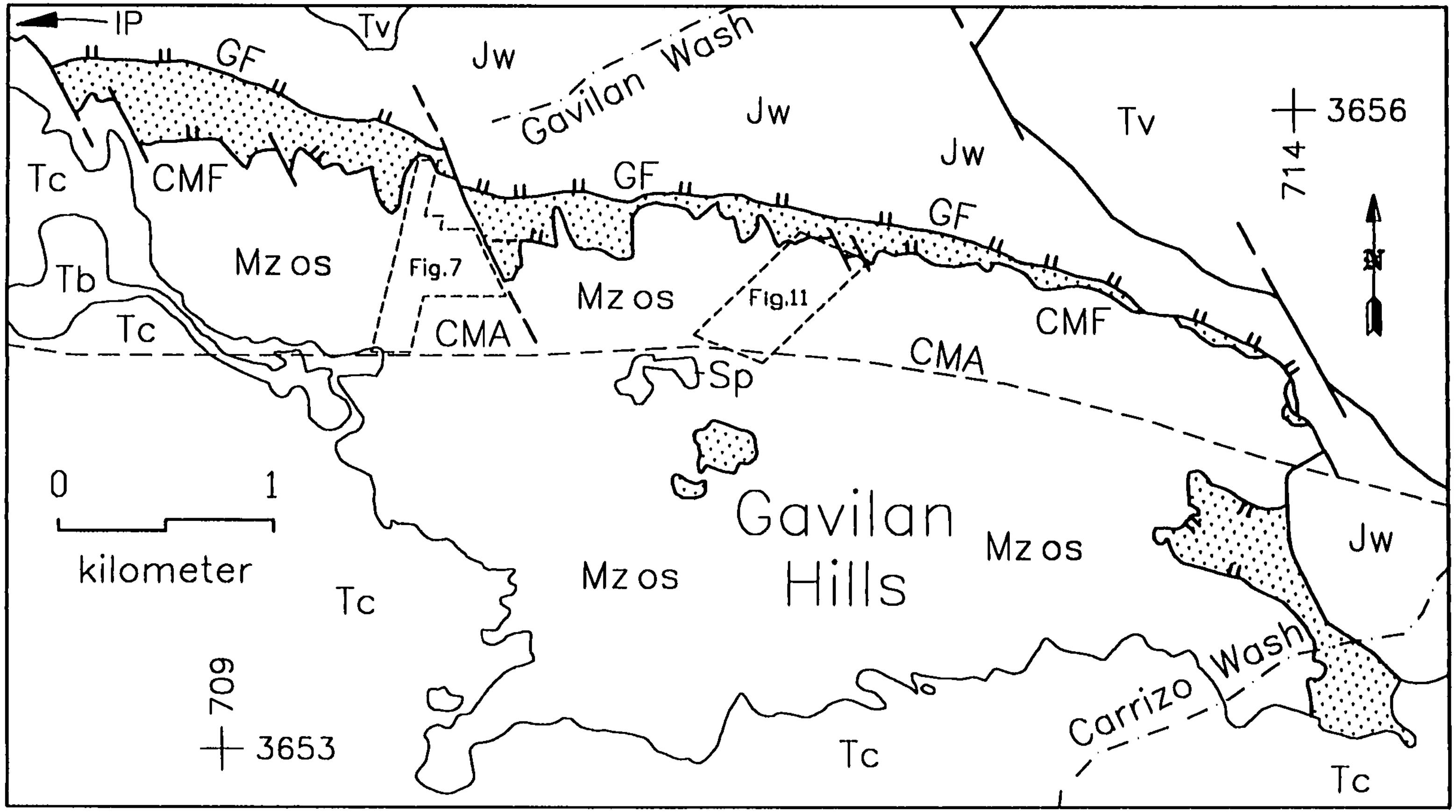

Figure 2. Geologic Map of the Gavilan Hills. Dashed line shows the trace of the Chocolate Mountains anticlinorium (CMA). Dotted pattern, upper plate rocks. IP, Indian Pass; GF, Gatuna fault; CMF, Chocolate Mountains fault; Mz os, Orocopia Schist; Sp, Serpentinite; Jw, Winterhaven Formation; Tv, Tertiary volcanics; Tc, Tertiary conglomerate (Miocene & Pliocene); Tb, Tertiary basalts (Miocene). Contacts after Haxel (1977) and this study. Crosses indicates Universal Transverse Mercator (UTM) grid.

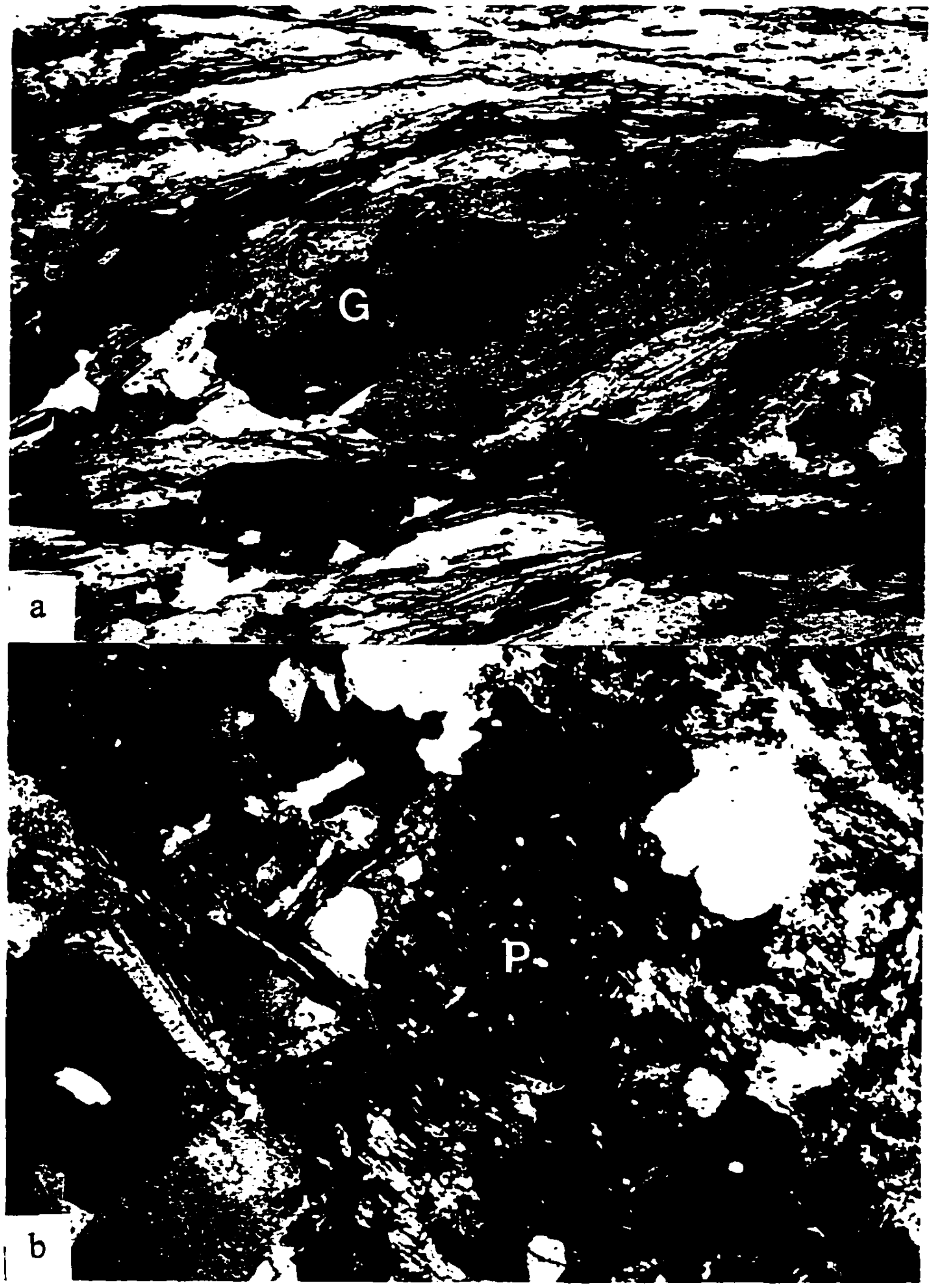

Figure 3. (a) Metagraywacke showing partial replacement of garnet (G) by chlorite (C). Width of field is 2.7 mm. Light is plane polarized. (b) Upper-plate gneiss showing plagioclase grain (P) being replaced by sericite and saussurite. To the left, grains of biotite show partial replacement to chlorite. Width of field is 2.7 mm. Light is cross polarized.

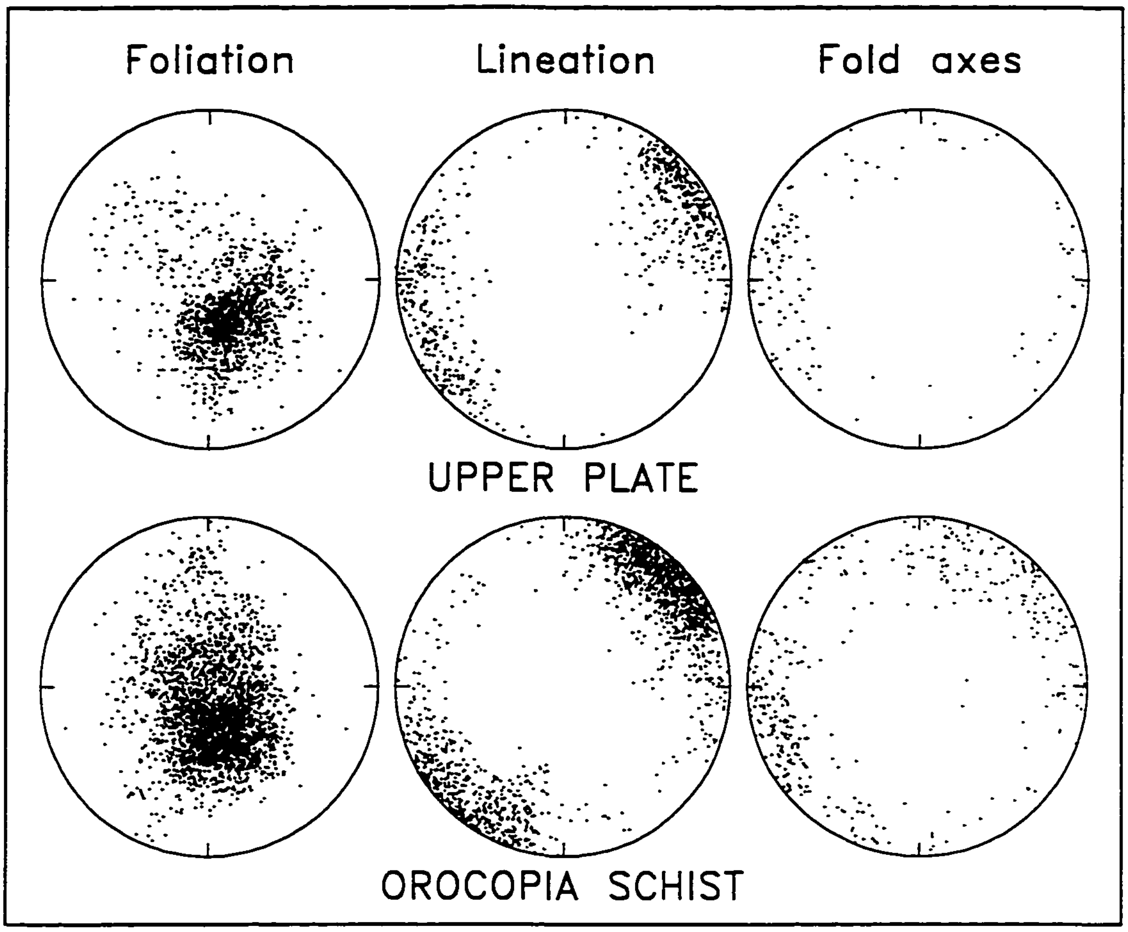

Figure 4. Orientations of foliation, lineation and fold axes in the Gavilan Hills area. All stereonet plots in this and subsequent figures are lower-hemisphere, equal-area projections with north at the top.

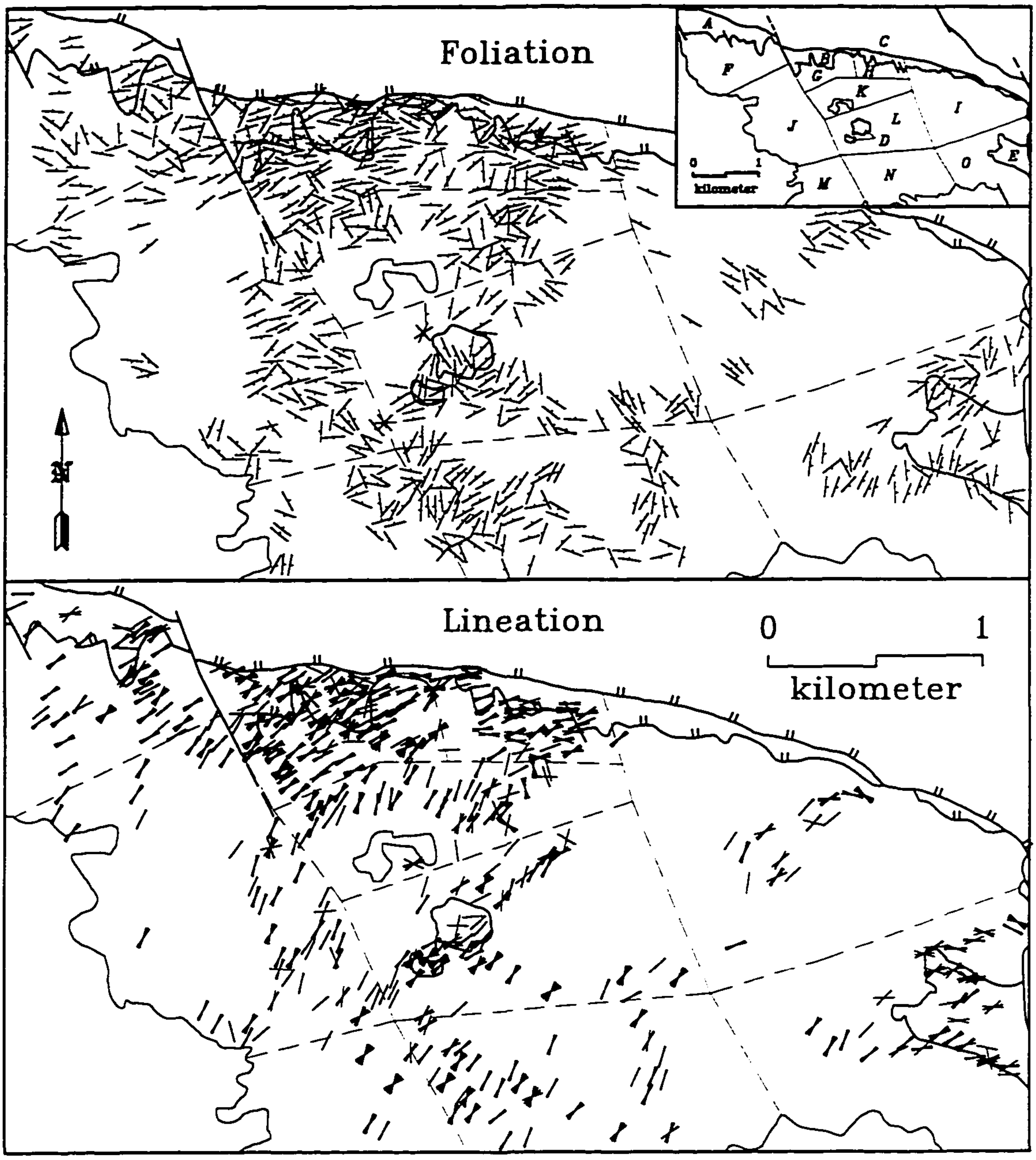

Figure 5. Maps of foliation and lineation in the Orocopia Schist and upper plate rocks. Arrowheads indicating direction of plunge are ommited in the lineation for clarity. Upper inset shows subareas discussed with reference to figures 6 and 10.

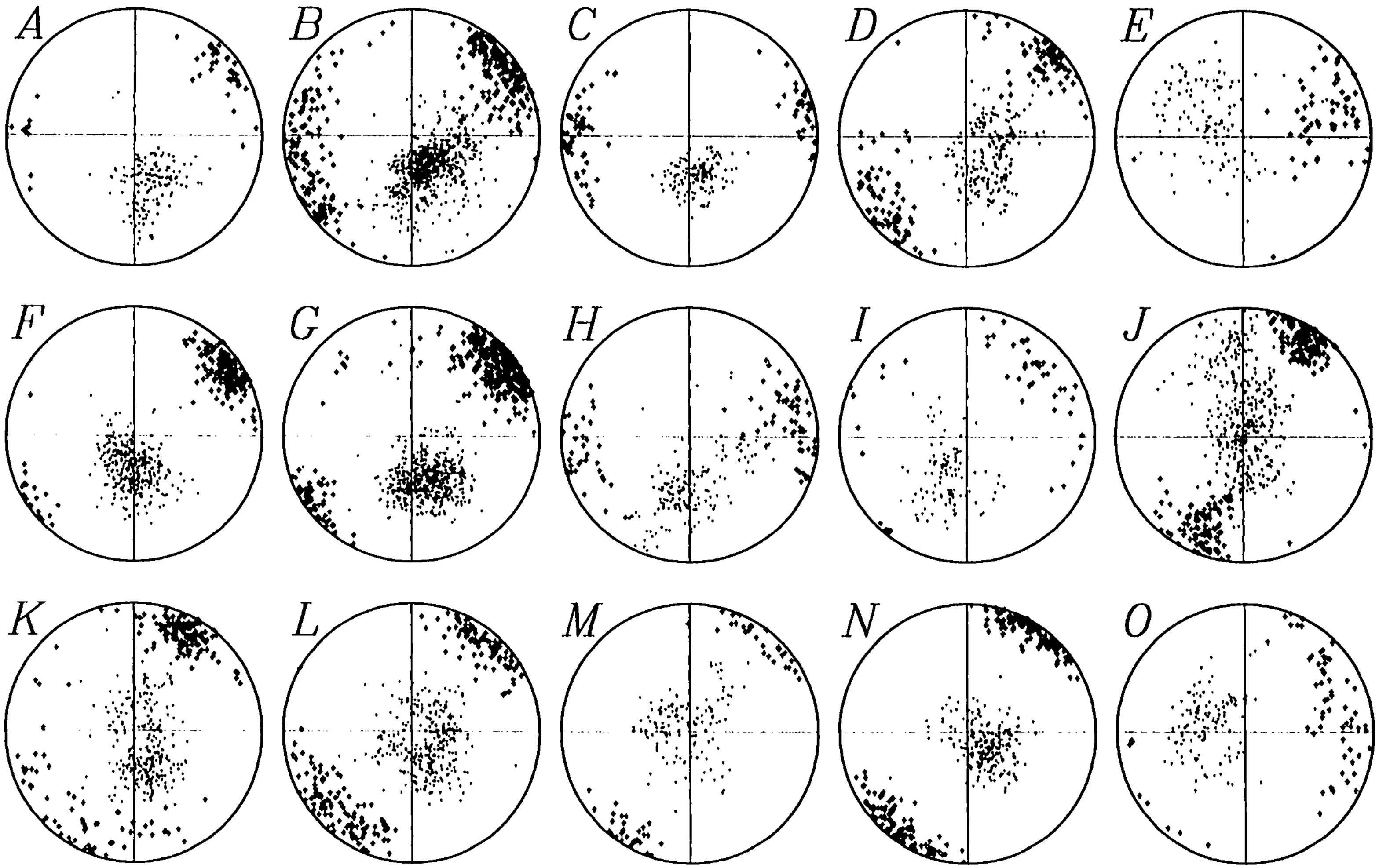

Figure 6. Orientations of foliation (dots) and lineations (pluses) for subareas A to O defined in Fig. 5. Areas A to E are in the upper plate, areas F to O are in the Orocopia Schist.

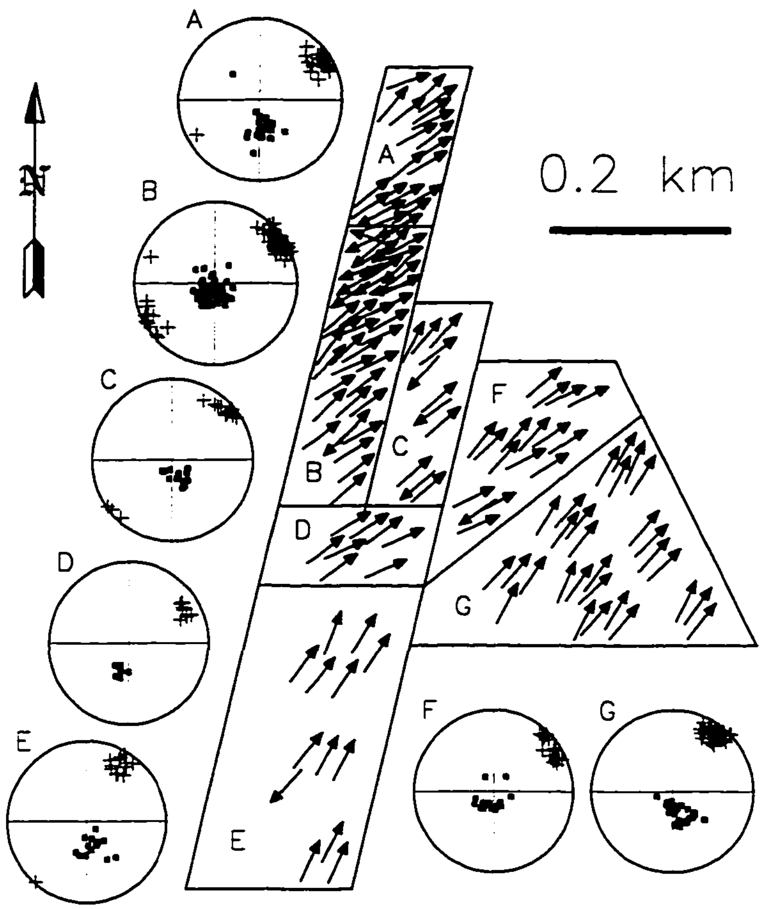

Figure 7. Orientation of lineations and foliation for Orocopia Schist in the NW section of the Gavilan Hills. Arrows in map indicate lineations. Foliation (filled squares) and lineation (pluses) are shown for each site in the stereonet plots. See Fig. 2 for location.

Figure 8. (a) Mylonite with well-developed quartz ribbons in a type II shear zone, Orocopia Schist. (b) Early (S_1) and late (S_2) foliations in a type II shear zone, Orocopia Schist. Width of field for both microphotographs is 2.7 mm. Light is cross polarized.

Figure 9. (a) Type II shear zone in upper plate gneiss, exhibiting fine ribbons of ductile deformed quartz alternating with layers of brittlely deformed plagioclase.
(b) Ductile deformed quartz and brittlely deformed plagioclase from shear zone at the top of the upper plate, adjacent to the Gatuna fault. Width of field for both microphotographs is 2.7 mm. Light is cross polarized.

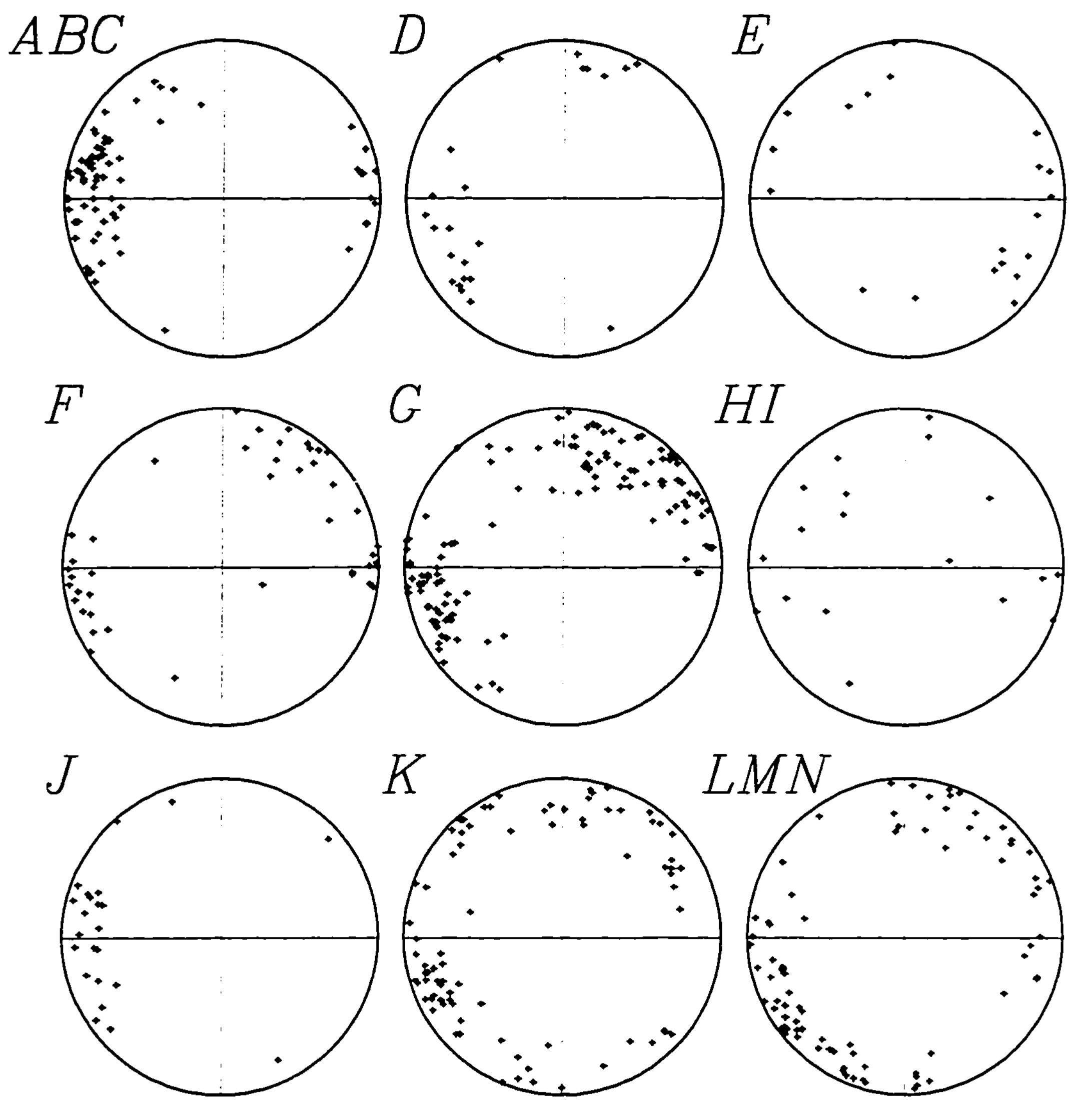

Figure 10. Stereonet plots of late folds in subareas A to N of figure 5.

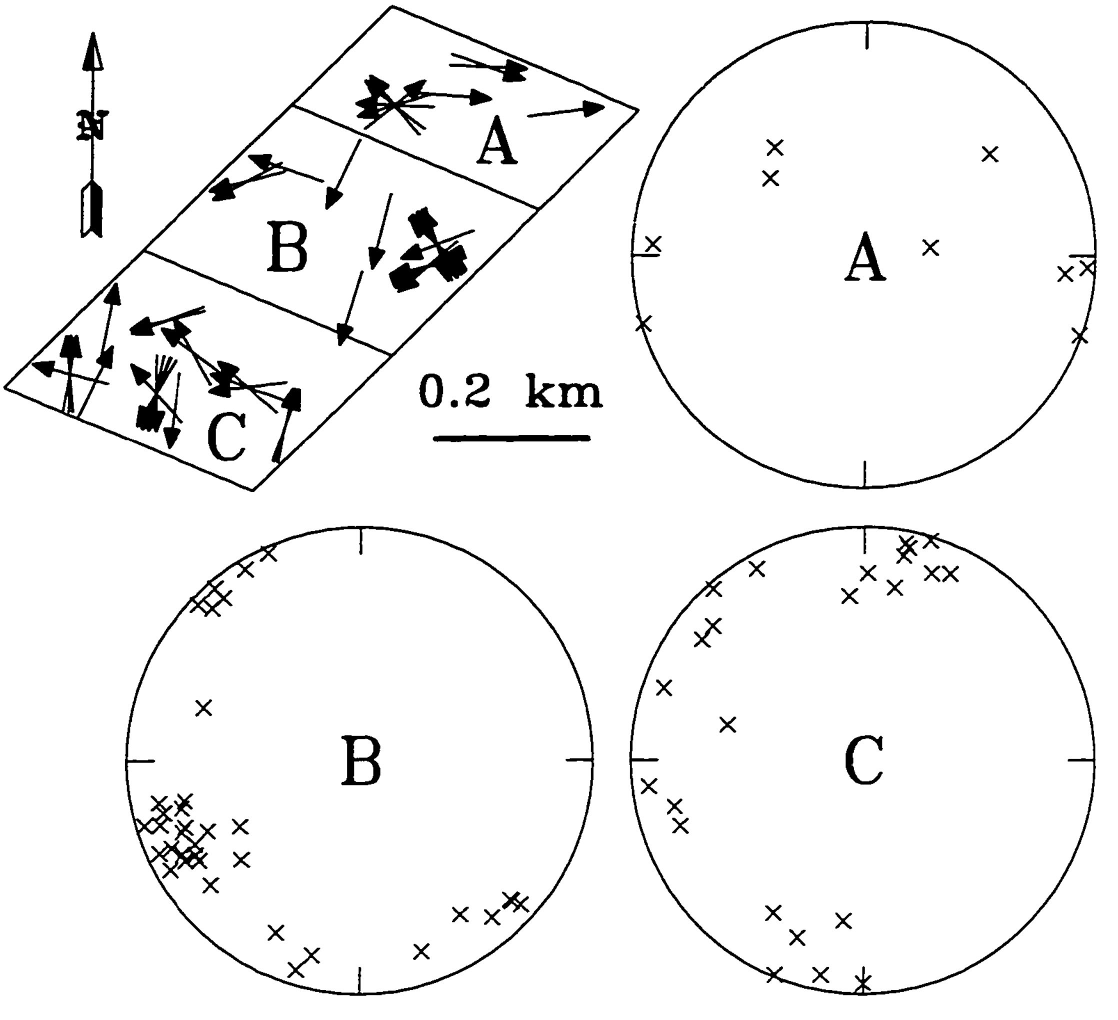

Figure 11. Distribution of folds in an area located structurally high. Arrows in the figure are fold axes. Stereonets plots of fold axes for each subarea. See Fig. 2 for location.

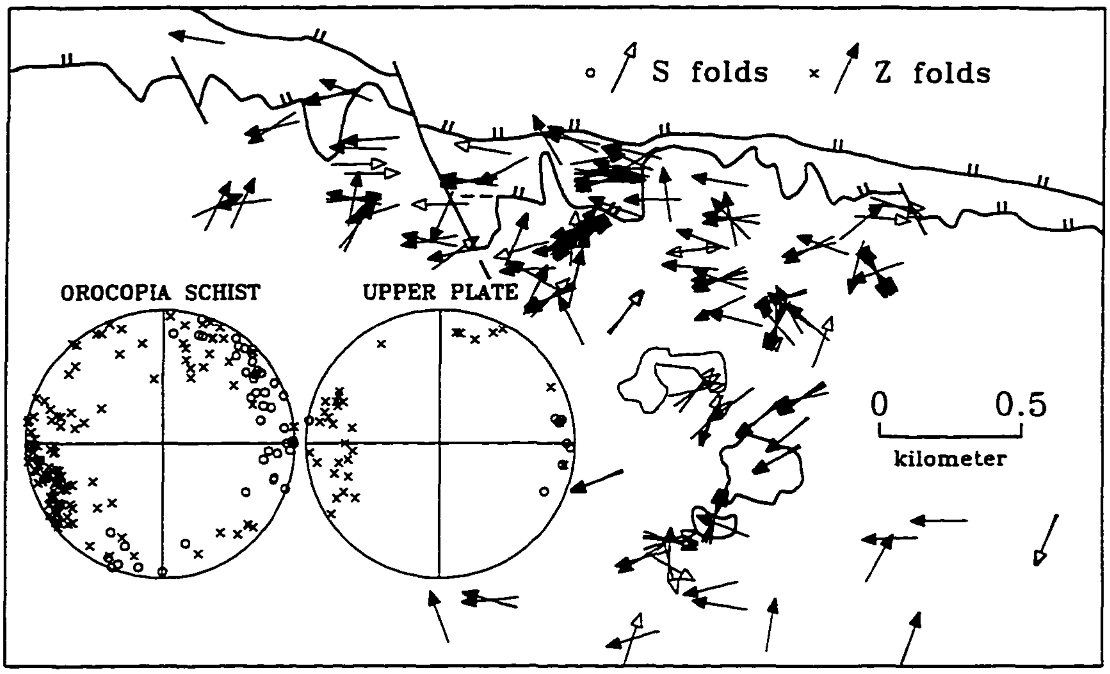

Figure 12. Folds with sense of asymmetry for the Orocopia Schist and upper plate. A few folds located in the SE corner of the area are not included in the map but are plotted in the stereonets.

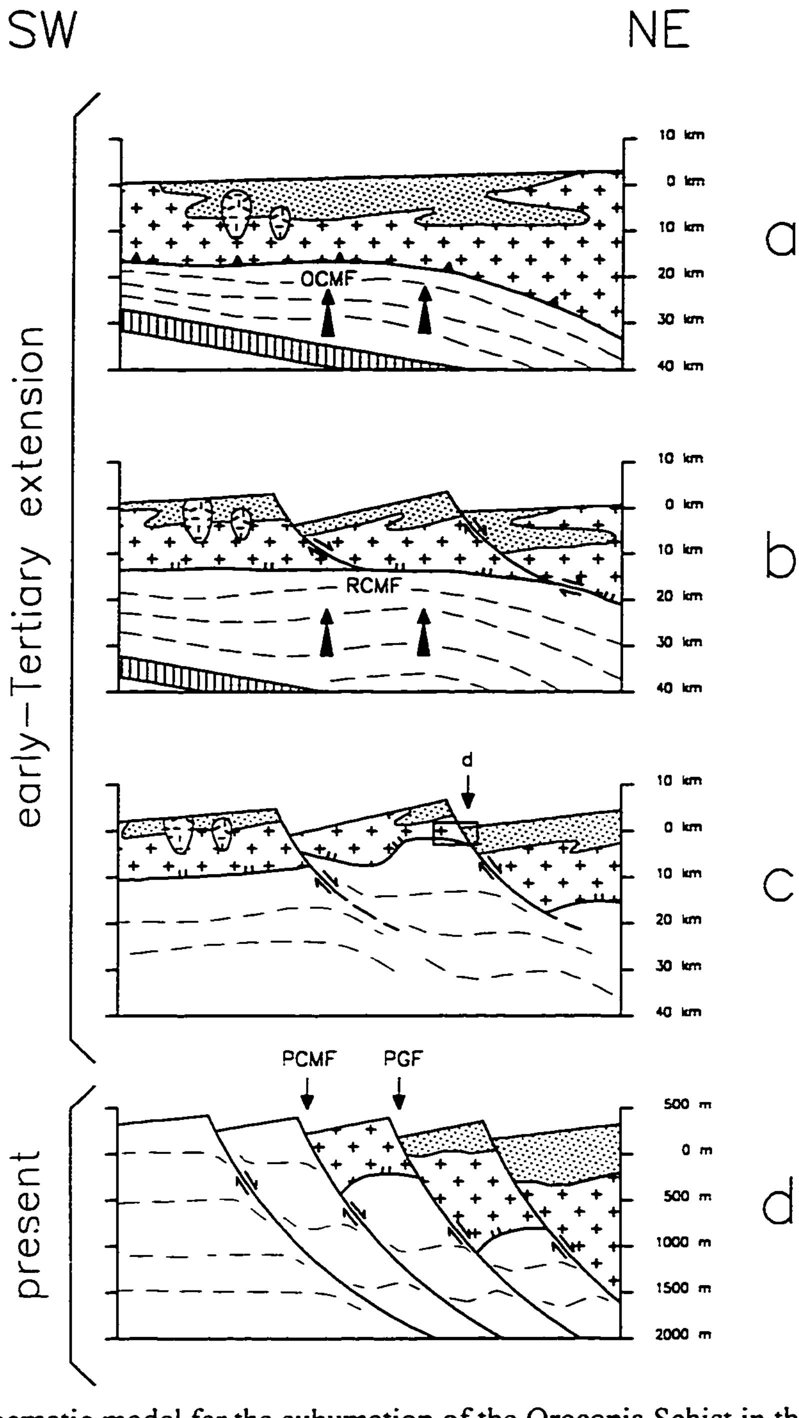

Figure 13. Schematic model for the exhumation of the Orocopia Schist in the Gavilan Hills. OCMF, original Chocolate Mountains fault; RCMF, reactivated Chocolate Mountains fault; PCMF, present Chocolate Mountains fault; PGF, present Gatuna fault. Barbs indicate the original contact between the Orocopia Schist and upper-plate gneisses before initiation of exhumation. See text for reference. Dotted pattern; Winterhaven Formation; crosses, upper plate; dash pattern, Mesozoic intrusives.

ESTIMATION OF METAMORPHIC CONDITIONS ACROSS THE CHOCOLATE MOUNTAINS FAULT IN THE GAVILAN HILLS OF SOUTHEASTERN CALIFORNIA: EVIDENCE OF POST-SUBDUCTION REACTIVATION

Felix R. Oyarzabal and Carl E. Jacobson

A paper to be submitted to *Journal of Metamorphic Geology*

Abstract

The Chocolate Mountains fault in southeastern California has been considered the original structure that underplated oceanic Orocopia Schist beneath plutonic and metamorphic rocks of the continental U.S. Estimations of pressure and temperature of metamorphism in both plates of the fault in the Gavial Hills show a gap in metamorphic conditions indicative of post-subduction reactivation. Garnet-biotite and garnet-hornblende geothermometry show that the Orocopia Schist originated at a lower temperature than the upper plate. Pressure determinations using the phengite and garnet-hornblende-plagioclase barometers confirm a subduction-complex origin for the Orocopia Schist. Amphibole compositional parameters show that the schist have originated at a lower temperature and at higher pressure than the upper plate. The petrological evidence agrees with structural observations that the Chocolate Mountains fault has undergone substantial post-metamorphic reactivation and that the present contact between the Orocopia Schist and upper plate records exhumation rather than subduction.

Introduction

The Chocolate Mountains fault is part of the regional Vincent-Chocolate Mountains (VCM) fault system of southern California and southwesternmost Arizona, which separates a lower plate of oceanic Pelona-Orocopia-Rand (POR) schist from an upper plate of igneous and metamorphic rocks of continental affinity. The POR schist is generally considered to be a Late Cretaceous-early Tertiary subduction complex, although a long-standing controversy exists regarding the geometry of subduction. Evidence of northeast transport of upper-plate rocks from several segments of the Chocolate Mountains fault in southeastern California suggests a tectonic setting in which an outboard continental fragment collided with North America along a southwest-dipping subduction zone (Haxel & Dillon 1978. Ehlig 1981. Vedder et al. 1983, Haxel & Tosdal 1986, Dillon et al. 1990). The collisional model has been criticized, however, because it is inconsistent with a number of regional geologic relations. A different view is that the structures indicative of NE transport are a late feature unrelated to subduction of the schist. In this latter view, the POR is a lateral equivalent of the Franciscan complex and formed during low-angle, east-directed subduction during the Laramide orogeny (Yeats 1968, Burchfiel & Davis 1981. Crowell 1981. Dickinson 1981. Hamilton 1987, 1988).

Several fragments of the VCM fault system have been interpreted as extensional faults with significant post-subduction reactivation (Frost et al. 1982. Haxel et al. 1985. 1988. Drobeck et al. 1986, Hamilton 1987. 1988. Jacobson et al. 1987. 1988. Postlethwaite & Jacobson 1987. Goodmacher et al. 1989. Dillon et al. 1990. Jacobson 1990. 1995. Jacobson & Dawson 1995. Oyarzabal *et al.* 1995). Recently, Simpson (1990) confirmed the northeast transport of upper-plate rocks along the Chocolate Mountains fault in part of the Gavilan Hills. but suggested that deformation had occurred during waning temperatures. To verify this conclusion we conducted a detailed structural and petrologic analysis to establish the timing of the NE phase of movement relative to the high-pressure metamorphism of the schist. This paper presents the results of the petrologic work, with the structural analysis to be published elsewhere (Oyarzabal *et al.* 1997).

Electron microprobe studies to estimate temperature and pressure (T and P) of metamorphism were carried out on both the Orocopia Schist and upper-plate rocks. A concordance of metamorphic conditions for rocks of both plates along the Chocolate Mountains fault would be expected if the original subduction-related structure is preserved. Alternatively, a gap in metamorphic conditions would occur if the original structure was reactivated as an extensional fault. The POR schist has long been regarded as a subduction complex and estimation of metamorphic conditions would help to constrain the origin of the schist, since mineral assemblages in this area are more suitable for quantitative barometry than assemblages found elsewhere. Quantitative estimates of T and P were obtained using garnet-biotite and garnet-hornblende thermometry and garnet-hornblende-plagioclase and phengite barometry whereas qualitative determinations were based on amphibole chemistry (Laird & Albee 1981). Amphibole compositions from mafic Orocopia Schist and upper plate amphibolites have been used in this study to compare metamorphic conditions for both structural units following the work of Jacobson (1997) and Jacobson & Dawson (1995) for the San Gabriel and Orocopia Mountains, respectively.

We conclude that upper-plate rocks formed at a higher T but lower P than the Orocopia Schist, indicating post-subduction reactivation of the Chocolate Mountains fault. The Orocopia Schist belongs to an intermediate- to intermediate-high pressure series whereas the upper plate corresponds to a lower pressure series. The Orocopia Schist in the Gavilan Hills shows a lower P/T ratio than other bodies of POR schist and metamorphic conditions suggest that it originated as a subduction complex.

Geologic and Structural Synthesis

The Gavilan Hills are located along a culmination of the Chocolate Mountains Anticlinorium, a regional structure that extends from the Chocolate Mountains to southwestern Arizona (Fig. 1, Haxel *et al.* 1985). The Orocopia Schist is the lowest tectonostratigraphic unit in the region and crops out in the core of the Gavilan Hills antiform (Fig 2). The upper plate constitutes a thin slice along the northern and eastern flanks of the Chocolate Mountains fault and forms two klippen in the central part of the area. The Jurassic? Winterhaven Formation, a supracrustal unit composed of low-grade metasedimentary and metavolcanic rocks, is in contact with the Orocopia Schist and upper plate rocks along the Gatuna fault, which dips moderately to steeply to the north.

The foliation in the Orocopia Schist defines a broad domal-structure elongated almost E-W. Two different structural domains are defined by the orientation of penetrative lineations. An older lineation trends NNE-SSW and is present at all structural levels. A younger lineation, trending ENE-WSW to E-W, is localized in a narrow area adjacent to the Chocolate Mountains fault. This region close to the fault is approximately 100 m thick and is characterized by structures oriented similarly to those in the upper plate but differently from ones in the structurally deep schist (Oyarzabal *et al.* 1997). Another important structural aspect of the schist is the presence of shear zones. We divide them into two end-members for ease of description, but a complete transition exists between them. Type I shear zones are the older of the two and occur throughout the sequence but are most abundant in the top 100 m of the section. They range from a few centimeters to several meters in thickness and their boundaries are generally parallel to the foliation in the surrounding schist. Type I shear zones contain at least two different foliations. The older one is similar to that present throughout the schist and is parallel to slightly oblique to the boundaries of the shear zone. This foliation is cut by shear bands (cf. Simpson & Schmid 1983; Lister & Snoke 1984), which are inclined to the boundaries of the shear zone. Most of the shear zones are composed of relatively coarse micas aligned along the older foliation. These domains are cut by thin shear bands showing grain size reduction. Although quartz and feldspar in both the coarse and fine areas are polygonal and strain free, the abundance of chlorite indicates that they are retrogressive in origin.

Type II shear zones cross cut the foliation of the schist at a moderate to high angle and are restricted to the top 100 m of the section. These shear zones are characterized by mylonitic textures as opposed to crystalloblastic ones. The youngest foliation is mylonitic and parallel to the boundaries of the shear zone. Textures range from protomylonitic to ultramylonitic in some shear zones but are uniformly ultramylonitic in other. The abundance of chlorite and the presence of a green biotite that has a lower Ti content than the prograde biotite indicate that the shear zones originated during retrogression of the mineral assemblage. Although evidence of ductile deformation is widespread in type II shear zones, many of them have been overprinted to a varying degree by cataclastic zones and fractures. The cataclastic overprint becomes stronger toward the top of the section. In both types of shear zones, the geometry of the foliations, as well as microstructural indicators, shows clear top-to-the-ENE to top-to-the-E sense of transport.

Shear zones and mylonites with similar structural orientation to those in the schist occur in the upper plate and also developed during retrograde metamorphism. These structures are overprinted by fractures and cataclastic zones, which are more common at the top of the section, where a cataclastic zone up to 10 m thick is located along the Gatuna fault. This fault was previously considered a brittle, middle Tertiary structure by Haxel et al. (1985), but a closer looks reveals that it originated under a ductile regime, and is probably coeval with the early reactivation of the Chocolate Mountains fault. The present contact between the Orocopia Schist and upper plate is a complex structure composed of moderately to steeply-dipping normal faults located along one of the shear zones. This observation confirms the reactivated character of the Chocolate Mountains fault that exposes an increase of brittle deformation toward structurally higher levels (Oyarzabal *et al.* 1997).

Electron Microprobe Techniques

Biotite, chlorite, garnet, feldspar, muscovite and epidote were analyzed using an ARL SEMQ electron microprobe at Iowa State University equipped with the Micro-3WD automation system developed at the University of California, Berkeley (Donovan & Rivers 1990). A slightly defocused beam (about 5 microns in diameter) was used for all analyses to prevent sample volatilization. Analytical conditions were 15 kilovolts acceleration voltage and 20 nanoamps sample current. A counting time of 40 seconds was used for most of the minerals except for some feldspars and epidotes, which we counted for 20 seconds in order to collect a large number of analyses to assess chemical zonation. Corrections were applied for background and dead time. Interelement and matrix corrections were performed using the ZAF procedure. Standards included a variety of analyzed minerals. Ferric iron content of calcic amphibole was estimated using the "maximum ferric iron" technique of Papike et.

al (1974). Iron was assumed to be all ferric in epidote and all ferrous in the remaining minerals.

Rock Types and Mineral Assemblages

More than 570 samples were collected Across the Gavilan Hills area and around 480 thin section were used to characterized the mineral assemblages. A set of 56 samples, 33 from the Orocopia Schist and 23 from the upper plate, was selected for electron microprobe studies.

Orocopia Schist

The Orocopia Schist in the Gavilan Hills is composed predominantly of metagraywacke (95%), with associated metabasalt, quartzite, marble and serpentinite. The prograde assemblage in the metagraywacke is composed of quartz, biotite, muscovite, oligoclase and/or albite, microcline, epidote, and garnet, with titanite, opaque, graphite, apatite, rutile, and zircon as additional components. One of the distinctive textural features of the schist is the presence of porphyroblast of oligoclase and/or albite that have a gray color due to graphite inclusions. Plagioclase grains are generally zoned, with albite rims and oligoclase cores, although homogeneous albite or oligoclase grains are also common. Garnet is present in about 50% of the samples as small grains in the matrix. The main components are almandine and grossular which generally account to more than 80 mole %. Garnet grains are weakly zoned with rims slightly richer in almandine and grossular and a core richer in spessartine (up to 12 mole % than the rims). Microcline is present in about 20% of the samples, as anhedral grains in the matrix of the metagraywacke, and it is relatively abundant in comparison with other exposures of the POR schist. Biotite is the most common mica in the schist of the Gavilan Hills, contrary to the Rand, San Gabriel and Orocopia Mountains, where it is less abundant than muscovite. Muscovite is a common component and shows a homogeneous composition through the region. The relative abundance of biotite + K-feldspar in the metagraywacke of this area could be due to low-Al bulk composition or to a higher metamorphic grade in the Gavilan Hills than in other exposures of the POR schist. Retrogression of the metagraywacke mineral assemblage is pervasive and widespread throughout the sequence, but is more conspicuous in shear zones and the zone of deformation associated with the Chocolate Mountains fault, and is reflected in the common replacement of garnet and biotite by chlorite (Fig. 3a) and oligoclase margins by albite (Fig. 3b).

The mafic schist is composed mostly of amphibole, plagioclase and epidote. Additional components are garnet, biotite, titanite, rutile, apatite, opaque and zircon. The amphibole is magnesio- to tschermakitic hornblende (Fig. 4). The plagioclase is generally zoned with cores of oligoclase and rims of albite (Fig. 5), although some samples contain only albite grains. Plagioclase is generally poikiloblastic with inclusions trails of one or several of the minerals quartz, hornblende, garnet, biotite, titanite and epidote. Figure 6a shows the average epidote composition, which is zoned with cores enriched with Fe and rims richer in Al. Garnet is present as inclusions in plagioclase and less commonly as fine to coarse grains in the matrix. Almandine and grossular are the main components and they amount to more than 70 mole %. In general, garnet in the mafic schist show a stronger zoning pattern than garnet in the metagraywacke with rims richer in almandine and grosssular and cores richer in spessartine. Based on the presence of Ca-bearing plagioclase and aluminous hornblende, prograde mineral assemblages in the Orocopia Schist belong to the lower amphibolite facies (oligoclase-amphibolite facies of Graham & Powell 1984). Retrogression of the prograde assemblage is extensive and includes (1) replacement of hornblende by actinolite and oligoclase by albite, (2) chloritization of hornblende, epidote and rare matrix garnet, (3) the fact that garnet is common as inclusion in plagioclase despite being rare in the matrix and (4) saussuritization of plagioclase.

Quartz veins are common throughout the sequence. Some are concordant with foliation in the schist others cut the foliation at low to high angles. One distinctive set of veins is composed of quartz, plagioclase and a blue fibrous amphibole of riebeckitic composition. These veins occur locally in the eastern part of the Gavilan Hills and cross-cut the foliation at a high angle. Commonly, crocidolite impregnates the schist for up to 10 cm away from the vein.

Upper plate

Predominant rock types in the upper plate are tonalitic to granitic gneiss (hereafter referred to as felsic gneiss), amphibolitic gneiss and amphibolite. The prograde assemblage of the felsic gneiss is composed of variable proportions of quartz, plagioclase, microcline, biotite and epidote with garnet and amphibole locally important. Plagioclase composition generally ranges between An_{20} and An_{40} (Fig. 7). Biotite is present in two distinctive generations, as brown to olive-green grains in the matrix of the gneiss and as very fine, green grains in rocks associated with shear and fault zones. Titanite, apatite, zircon and rutile are present in most of the samples. The amphibolite consists of subequal proportions of hornblende and plagioclase, with quartz, garnet, epidote and biotite as additional components. Epidote in the gneisses has higher Fe^{3+} content than epidote in the schist (Fig. 6b). Titanite, opaque, apatite, rutile and zircon are present in most of the samples. On average, amphibole in the amphibolite is more pargasitic than amphibole in the Orocopia Schist (Figs. 4 & 8). Anorthite content of plagioclase in the amphibolite ranges mostly between 20 and 40 mole percent (Fig 7), but could be as high as 60 mole percent. Plagioclase compositions lower than An_{20} are part of the retrograde assemblage. The amphibolitic gneiss is intermediate in composition between the amphibolite and the felsic gneiss. The above mineral assemblages are indicative of peak-metamorphic conditions in the middle amphibolite facies.

Retrogression of upper-plate assemblages to greenschist facies is pervasive and extends throughout the section, but is particularly important at the base and top of the upper plate, and along the shear zones. Common features of the retrogressive overprint are (1) rimming of hornblende by actinolite (Fig 9a), (2) rimming of oligoclase by albite, (3) chloritization of garnet, hornblende, and biotite (Fig. 9b & 10a), (4) extensive sericitization, muscovitization and saussuritization of plagioclase (Fig. 10b). Some of the epidote also seems to be secondary. Veins containing crocidolite and aegirine, with similar areal distribution to the ones described for the schist, are also common in the upper plate. Their presence in both structural units indicates that they formed at a late-stage, but their origin is elusive.

Thermobarometry in the Gavilan Hills

Calcic amphibole as an indicator of metamorphic conditions

Calcic amphibole is stable under a wide range of environmental conditions and its chemistry is dependent upon bulk composition and mineral assemblage. Laird & Albee (1981), in their landmark study of three contrasting metamorphic terranes in Vermont, demonstrated that the composition of amphibole in mafic schist is a good indicator of temperature and pressure of metamorphism when associated with a buffering assemblage which controls the extent of cation exchange. The buffering association, referred to as the "common" assemblage, consists of amphibole + chlorite + epidote + plagioclase + quartz + Ti phase ± carbonate ± K-mica ± Fe^{3+}oxide. The most important substitutions in calcic amphibole from the greenschist to amphibolite facies are edenite, glaucophane, and tschermakite, all of which increase with metamorphic grade (Miyashiro, 1973; Graham, 1974; Brown, 1977; Ernst, 1979; Laird, 1980, Laird & Albee, 1981). A series of plots displaying the relationship between different amphibole chemical parameters was generated by Laird & Albee (1981) who found a positive correlation between temperature of metamorphism and Al content (edenite and tchermakite substitution) and pressure and Na content (crossite substitutions). Specifically, the ratio Na#/Al#, where Na# = 100 x Na/(Na + Ca) and Al# = 100 x Al(Al + Si), was found to be directly dependent on metamorphic conditions. Those relationships have also been noticed by Cooper & Lovering (1970), Miyashiro (1973), Graham (1974), Brown (1977) and Ernst (1979).

Jacobson (1995) and Jacobson & Dawson (1995) found that the composition of calcic amphibole in the POR schist is a reliable indicator of relative metamorphic conditions. We analyzed amphibole from a number of samples of mafic Orocopia Schist and upper-plate amphibolites containing the "common" assemblages to estimate relative conditions of metamorphism for these rocks. One important factor that control amphibole composition is oxidation state, of which epidote is a good indicator. Figure 6a & b shows that Fe^{3+} content in both lithologic units is relatively similar. The epidote-albite projection (Fig. 11, cf. Laird 1980) gives an indication of the whole-rock $Mg/(Mg + Fe^{2+} + Mn)$ ratio for the schist and upper-plate rocks, and suggests that both units have similar bulk composition. Although a parallelism exists between the garnet-chlorite tie-lines and the amphibole-chlorite tie-lines in the schist, textural evidence indicates that the chlorite is retrograde. It also shows that amphibole in the Gavilan Hills is more aluminous than amphibole in the greenschist facies of the Pelona Schist in the San Gabriel Mountains and in the epidote blueschist, greenschist and albite-epidote amphibolite facies of the Rand Schist in the Rand Mountains (Jacobson 1995, Figs. 9 & 10) which suggests a higher metamorphic grade in this area. A plot of Na# versus Al# for amphibole from the Orocopia Schist and upper plate is presented in Fig. 12, along with the fields for different facies series indicated by the data of Laird & Albee (1984). Amphibole compositions from prograde assemblages of upper-plate samples plot indicate a lower-pressure facies series than those from the Orocopia Schist. The plot of Na^{M4} against $Al^{VI} + Fe^{3+} + Ti$ incorporates a ferric iron correction and shows similar trends as the plots of Na# versus Al#. Plots of Ti and K versus Al^{IV} are presented in Fig. 13 from amphibole of both the Orocopia Schist and upper plate. Contents of Ti and K shows a positive correlation to metamorphic temperature (Leake 1965, Cooper & Lovering 1970). These plots clearly show that amphibole in the upper plate has Ti and K contents indicative of a higher temperature than the Orocopia Schist.

Garnet-biotite thermometry

The simplest calibrations for this thermometer assume ideal mixing of Fe and Mg in biotite and garnet (Ferry & Spear 1978, Perchuk & Lavrent'eva 1983). More elaborate calibrations take into account non-ideal mixing in garnet or in both minerals (Hodges & Spear 1982, Pigage & Greenwood 1982, Indares & Martignole 1985, Ganguly & Saxena 1984, Hoinkes 1986, Aranovich et al. 1988, Williams & Grambling 1990, Dasgupta et al. 1991, Bhattacharya et al. 1992, Kleemann & Reinhardt 1994). Garnet composition in the range of those used in the calibrations is one of the most important constraints of this thermometer. The presence of Ca and Mn in garnet affects the Fe-Mg mixing behavior and some calibrations have been formulated to compensate for those impurities.

Chemical compositions for ten garnet-biotite pairs from both the Orocopia Schist and upper-plate samples are presented in table 1. Most of the samples have garnets with high grossular and spessartine components, which indicates the necessity of calibrations that will account for these impurities. Garnet-biotite temperatures using six different calibrations are shown in table 2. The highest almandine component from the garnet rim and the average biotite composition were used in the calculations. The analyzed grains were chosen from prograde assemblages (Fig. 14a) and grains showing replacement by chlorite or other signs of retrogression were carefully avoided. Pressures of 8 kbars were assumed for both the Orocopia Schist and upper plate. In general, thermometers that do not account for components other than Fe-Mg in garnet (calibrations 1 & 2) result in lower temperatures than those that do. Calibrations that utilize complex solution models for garnet (Calibrations 2 to 6) result in temperatures that are comparable to those obtained using the garnet-hornblende thermometer (see below). Among the calibrations that account for non-ideal mixing in both garnet and biotite, the thermometer of Kleeemann & Reinhardt (1994) has the smallest intersample temperature range with 90° C for the Orocopia Schist and 61° C for upper plate rocks. This latter calibration accounts for the presence of Al^{VI} and Ti in biotite and uses the garnet activity model of Bergman (1990). The most important observation from these calculated temperatures is that, regardless of the calibration used, the rocks of the upper plate appear to have crystallized at substantially higher temperature than the Orocopia Schist not only at similar pressures but also at pressures of 9 to 10 kbars in schist.

Garnet-hornblende thermometry

Graham & Powell (1984) calibrated an empirical thermometer based on Fe-Mg partitioning between garnet and hornblende. This geothermometer uses a regular solution model for non-ideal mixing behavior of Ca in garnet and assumes that all Fe in hornblende is ferrous. This pressure-independent thermometer is best suited for rocks that form below 850° C, have low activity of water and contain garnet with low Mn content (Graham & Powell 1984). The thermometer has been tested in mafic Pelona Schist from the Sierra Pelona and has yielded temperatures of about 480° C for the garnet isograd, 570° C for the oligoclase isograd and 620-650° C near the Vincent thrust (Graham & Powell 1984).

Application of this thermometer to amphibolites in the Orocopia Schist from the

Gavilan Hills (Fig. 14b) yields temperatures in the range of 503 to 606° C. Six out of eleven samples have temperatures below the 570° C, which is the temperature determined by Graham & Powell (1984) for the oligoclase isograd. The average garnet-hornblende temperature for the Orocopia Schist is up to 43° C higher than the average garnet-biotite temperature, excluding the simplest calibrations. Only a few samples of amphibolite from the upper plate contain garnet, and most of them exhibit textural disequilibrium. Two upper-plate samples that were analyzed yielded temperatures of 654 and 792° C.

Phengite Geobarometry

Experimental studies conducted on muscovite by Velde (1965) and Massone & Schreyer (1987) have shown that Si content of muscovite is strongly pressure-dependent. Several geobarometers using thermodynamic and empirical calibrations have been proposed for muscovite-bearing metapelites and metapsammites (Velde 1967, Powell & Evans 1983, Bucher-Nurminen 1987, Massone & Schreyer 1987). The maximum Si content of phengite is attained in the presence of the limiting assemblage K-feldspar, quartz and a trioctahedral mica (Massone & Schreyer 1987). The Si content of muscovite was determined for six metagraywackes from the Orocopia Schist in the Gavilan Hills and two gneisses from the upper plate containing the association microcline + muscovite + biotite + quartz. There is no significant variation in the silica content of both lithologic units. Pressures estimates for the Orocopia Schist at 570° C range from 6.5 to 11.0 kbars (Fig. 15). Contrary to the schist, muscovite in upper plate rocks formed mostly during retrogression and their use as pressure indicators is difficult. Two gneisses yield pressures of about 7.0 to 7.8 kbars at an estimated temperature of 400° C and 6.2 to 6.8 kbar at 350° C.

Garnet-hornblende-plagioclase geobarometry

Kohn & Spear (1990) developed two geobarometers for the assemblage garnet-hornblende-plagioclase-quartz based on the reactions:

6 anorthite + 3 tremolite $\Leftrightarrow$ 2 grossular + 1 pyrope + 3 tschermakite + 6 quartz

6 anorthite + 3 Fe-actinolite $\Leftrightarrow$ 2 grossular + 1 almandine + 3 Fe-tschermakite + 18 quartz

The calibration uses the Hodges & Royden (1984) anorthite activity model and the Hodges & Spear (1982) garnet activity model, with partial-local charge balance for amphibole activity. The calibration does not account for non-ideal mixing in amphibole. Consistency with other barometers is on the order of ± 2 kbar.

A small set of samples from the Gavilan Hills complies with the compositional constraints imposed by this calibration. Estimated pressures from four schist and one upper-plate rock, along with some compositional parameters of the phases involved, are shown in table 4. Some of the pressure estimates are similar to the average pressures obtained with the phengite barometer on the Orocopia Schist and some are higher. The upper-plate sample yielded a lower pressure than the schist. A map of temperature and pressure distribution for the different geothermometers and geobarometers is presented in Fig. 16.

Discussion

Determination of pressure and temperature of metamorphism for rocks of the Orocopia Schist and upper plate by traditional methods is difficult due to (1) lack of suitable assemblages, (2) mineral compositions outside the range of calibrants and (3) uncertainties regarding the extent of retrogression. Nonetheless, systematic differences in metamorphic temperatures and pressures between the Orocopia Schist and the upper plate of the Chocolate Mountains are evident. These differences are independent of the chosen geobarometer or geothermometer.

Amphibole-bearing rocks are widespread in the POR schist and upper plate allowing the application of quantitative and qualitative approaches to thermobarometry in the same set of samples. Amphibole compositions in the mafic schist and amphibolites and gneisses of the upper plate have been used to determine relative P-T conditions for exposures in the San Gabriel and Orocopia Mountains (Jacobson & Dawson 1995, Jacobson 1997). In the Orocopia Mountains, a gap in amphibole composition between the schist and the upper plate indicates that the Orocopia fault has undergone post-metamorphic reactivation. In contrast, amphibole in the San Gabriel Mountains shows a continuous compositional trend from the Pelona Schist to a retrograded mylonite zone located at the base of the upper plate, suggesting that the Vincent Fault is a preserved fragment of the VCM "thrust" (Jacobson, 1997). In the Gavilan Hills, amphibole compositional parameters show different trends between Orocopia Schist and upper-plate rocks. The composition of amphibole in mafic rocks indicates that the Orocopia Schist belongs to a higher-P facies series than the upper plate, but that the upper plate originated at higher temperatures (Figs. 12 & 13).

Garnet-hornblende thermometry indicates temperatures of around 550° C for the Orocopia Schist. Garnet-biotite thermometry is applicable to rocks from the Gavilan Hills only if the non-ideality of Ca and Mn in garnet and Al^{VI} and Ti in biotite are accounted for in the Fe-Mg mixing behavior of both phases (cf. Kleemann & Reinhardt 1994).

Temperature estimation from calibrations with complex solution models for garnet alone or both garnet and biotite (calibrations 3 to 6 of table 1) yield comparable results to those obtained from the Orocopia Schist with the garnet-hornblende thermometer. Mineral assemblages indicate that the Orocopia Schist belongs to the oligoclase-amphibolites facies. but the estimated temperatures of about 550° C seem to indicate that most of the section has been affected by retrogression or that equilibrium was not achieved during peak-metamorphic conditions.

Garnet-biotite thermometry in upper-plate samples shows a range of temperatures from 657 to 866° C (calibrations 3 to 6). The garnet-hornblende thermometer yields similar results in a couple of upper-plate amphibolites. These determinations indicate that the upper-plate rocks formed at 50 to 100° C higher than the schist. Upper-plate temperatures above 700° C are considered too high to be geologically reasonable. At about 700° C. partial melting of the felsic gneiss and amphibolites would be expected. even at low water contents (Fig. 17, Wyllie 1983), yet there is no field evidence of migmatization in the upper plate. The most important observation is that. regardless of the thermometer or calibration chosen. rocks of the upper plate appear to have crystallized at substantially higher temperatures than the Orocopia Schist.

According to the phengite geobarometer of Massone & Schreyer (1987). pressures of metamorphism in the Orocopia Schist range from 6.2 to 10.0 kbars assuming a temperature of 550 °C. Figure 15 shows two cluster of Si content in the analyzed muscovites. Three samples have muscovites with Si content between 3.20 to 3.24 whereas four samples have Si contents of 3.29 to 3.38. The lower silica content in some muscovites could be due to retrogression or disequilibrium, but petrographic evidence in this regard is inconclusive. If only the higher values are indicative of peak-metamorphic pressure, we can assume that the Orocopia Schist formed at 8 to 10 kbars. Graham & Powell (1984) obtained similar pressures from the schist of the Sierra Pelona, where the phengite calibration of Powell & Evans (1983) yielded 10±1 kbar and the jadeite content of clinopyroxene indicated 8-9 kbar. The garnet-hornblende-plagioclase barometer of Kohn & Spear (1990) gives pressures in the range of 9.3 to 11.8 kbars for the Orocopia Schist. Application of the garnet-hornblende-plagioclase barometer on an upper-plate rock resulted in pressures of 7.6 and 8.5 kbars for the Fe and Mg-end members respectively. The phengite barometer indicates lower pressures at substantially lower temperatures.

The P-T fields for Orocopia Schist and upper-plate rocks are shown in Fig. 17 along with some reactions lines and the melting curves of wet tonalite and amphibolite. Basic assumptions are (1) the prograde metamorphic temperature for the schist is above 500° C. (2) the pressure field for the schist is indicated by the higher Si content cluster of Fig. 15. (3) only temperatures below the wet-amphibolite melting curve are geologically reasonable for the upper plate and (4) muscovite in upper plate samples achieved equilibrium during retrogression at about 350 to 400° C. These calculated P-T conditions for the Orocopia Schist and upper plate samples show that the upper plate has formed at higher temperatures but lower pressures than the Orocopia Schist. These findings suggest that a gap in metamorphic conditions exists between both structural units and are in agreement with structural data indicating that part of the section is missing along the Chocolate Mountains fault (Oyarzabal *et al.* 1997). The discordance in metamorphic conditions supports the evidence that the VCM fault has been reactivated as an extensional fault in southeastern California. In this scenario, the structures with NE transport of upper plate are assigned to a post-subduction phase of deformation and have no implications in the tectonic setting, eliminating the need for the collisional model to explain the origin of the Orocopia Schist.

Acknowledgments

We have benefited from discussions with Andrew Barth, John Crowell, Perry Ehlig, Eric Frost, Gordon Haxel, Daniel May, Stephen Richard, and Paul Spry. Funding was provided by National Science Foundation grants EAR-9004354 and EAR-9316916 to Carl Jacobson.

References

Aranovich, L. Y., Lavrent'eva, I. V. & Kosyakova, N. A. 1988. Calibration of the biotite-garnet and biotite-orthopyroxene geothermometers corrected for the variable Al level in biotite. *Geochem. Int.* **25**, 50-59.

Bergman, R. G. 1990. Mixing properties of Ca-Mg-Fe-Mn garnets. *Am. Mineral.*, **75**, 328-344.

Bhattacharya, A., Mohanty, L., Maji, A., Sen, S. K. & Raith, M. 1992. Non-ideal mixing in the phlogopite-annite binary: Constraints for experimental data on Mg-Fe partitioning and a reformulation of the biotite-garnet geothermometer. *Contr. Miner. Petrol.* **111**, 87-93.

Brown, E. H. 1977. The crossite content of Ca-amphibole as a guide to pressure of metamorphism. *J. Petrol.* **18**, 53-72.

Bucher-Nurminen, K. 1987. A recalibration of the Chlorite-biotite-muscovite geobarometer. *Contr. Miner. Petrol.* **96** 519-522.

Burchfiel, B. C. & Davis, G. A. 1981. Mojave Desert and environs. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, New Jersey, 217-252.

Cooper, A. F. & Lovering, J. F. 1970. Greenschist amphiboles from the Hast River, New Zealand. *Contr. Miner. Petrol.* **27**, 11-24.

Crowell, J. 1981. An outline of the tectonic history of southeastern California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, New Jersey, 583-600.

Dickinson, W. R. 1981. Plate tectonics and the continental margin of California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, New Jersey, 1-28.

Dasgupta, S., Sengupta, P., Guha, D. & Fukuoka, M. 1991. A refined garnet-biotite Fe-Mg exchange geothermometer and its application in amphibolites and granulites. *Contr. Miner. Petrol.*, **109**, 130-137.

Dillon, J. T., Haxel, G. B. & Tosdal, R. M. 1990. Structural evidence for northeastward movement on the Chocolate Mountains thrust, southeasternmost California. *J. geophys. Res.* **95**, 19,953-19,971.

Donovan, J. J. & Rivers, M. L. 1990. PRSUPR: A PC based automation and data reduction software package for wavelength dispersive electron beam micro-analysis. In: *Proceedings of the XIIth International Congress for Eectron Microscopy*. San Francisco Press, Inc., San Francisco, 86-87.

Drobeck, P. A., Hillemeyer, F. L., Frost, E. G. & Liebler, G. S. 1986. The Picacho Mine: A gold mineralized detachment in southeastern California. *Ariz. geol. Soc. Dig.* **XVI**, 187-221.

Ernst, W. G. 1979. Coexisting sodic and calcic amphiboles from high-pressure metamorphic belts and the stability of barroisitic amphibole. *Mineral. Mag.* **43**: 269-278.

Ehlig, P. 1981. Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, New Jersey, 253-283.

Ferry, J. M. & Spear, F. S. 1978. Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contr. Miner. Petrol.* **66**, 113-117.

Frost, E. G., Martin, D. L. & Krummenacher, D. 1982. Mid-Tertiary detachment faulting in southwestern Arizona and southeastern California and its overprint on the Vincent thrust system. *Abs. with Progr. geol. Soc. Am.* **14**, 164.

Ganguly, J. & Saxena, S. 1984. Mixing properties of aluminosilicate garnets: constraints from natural and experimental data, and applications to geothermo-barometry. *Am. Mineral.* **66**, 88-97.

Goodmacher, J., Barnett, L., Buckner, G., Ouachrif, L., Vidigal, A. & Frost, E. 1989. The Clemens Well fault in the Orocopia Mountains of southern California: A strike-slip or normal fault structure?. *Abs. with Progr. geol. Soc. Am.* **21**, 85.

Graham, C. M. 1974. Metabasite amphiboles of the Scottish Dalradian. *Contr. Miner. Petrol.* **47**, 165-185.

Graham, C. M. & Powell, R. 1984. A garnet-hornblende geothermometer: calibration, testing, and application to the Pelona Schist, Southern California. *J. metamorph. Geol.* **2**, 13-31.

Hamilton, W. 1987. Crustal extension in the Basin and Range Province, southwestern United States. In: *Continental extensional tectonics*, (edited by Coward, M. P., Dewey, J. F., & Hancock, P. L.), *Spec. Publs. geol. Soc. Lond.* **28**, 155-176.

Hamilton, W. 1988. Tectonic setting and variations with depth of some Cretaceous and Cenozoic structural and magmatic systems of the western United States. In: *Metamorphism and Crustal Evolution of the Western United States* (edited by Ernst, W. G), Prentice Hall, New Jersey, 1-40.

Haxel, G. B. 1977. The Orocopia Schist and the Chocolate Mountain Thrust, Picacho-Peter Kane mountain area, southeasternmost California. Unpublished Ph.D. thesis, University of California, Santa Barbara, California.

Haxel, G. B. & Dillon, J. T. 1978. The Pelona-Orocopia Schist and Vincent-Chocolate Mountains Thrust System, Southern California. In: *Mesozoic Paleogeography of the Western United States* (edited by Howell, D. J. & McDougall, K. A.), *Society of Economic Paleontologists and Mineralogists*, Pacific Coast Paleogeography Symposium **2**, 453-469.

Haxel, G. B., Jacobson, C. E. & Tosdal, R. M. 1988. Multiple low-angle faults atop the Orocopia Schist, southwestern Arizona and southeastern California. *Abs. with Progr. geol. Soc. Am.* **20**, A383.

Haxel, G. B. & Tosdal, R. M. 1986. Significance of the Orocopia Schist and Chocolate Mountains thrust in the late Mesozoic tectonic evolution of the southeastern California-southwestern Arizona region: extended abstract. In: *Frontiers in Geology and Ore Deposits of Arizona and the Southwest* (edited by Beatty, B. & Wilkinson, P. A. K.), *Ariz. geol. Soc. Dig.* **16**, 282-293.

Haxel, G. B., Tosdal, R. M. & Dillon, J. T. 1985. Tectonic Setting and lithology of the Winterhaven Formation: A new Mesozoic stratigraphic unit in southeasternmost California and southwestern Arizona. *Bull. U.S. geol. Surv.* **1599**, pp. 19 pp.

Hodges, K. V., & Royden, L. 1984. Geologic thermobarometry of retrograde metamorphic rocks: an indicator of the uplift trajectory of a portion of the northern Scandinavian Caledonides. *J. geophys. Res.* **89**, 7077-7090.

Hodges, K. V. & Spear, F. S. 1982. Geothermometry, geobarometry and the Al2SiO5 triple point at Mt. Moosilauke, New Hampshire. *Am. Mineral.* **67**, 1118-1134.

Hoinkes, G. 1986. Effect of grossular-content in garnet on the partitioning of Fe and Mg between garnet and biotite. *Contr. Miner. Petrol.* **92**, 393-399.

Holland, T. J. B. 1980. The reaction albite = jadeite + quartz determined experimentally in the range 600-1200° C. *Am. Mineral.* **65**, 129-134.

Holland, T. J. B. 1983. The experimental determination of activities in disordered and short-range ordered jadeitic pyroxenes. *Contr. Miner. Petrol.* **82**, 214-220.

Indares, A. & Martignole, J. 1989. The greenville front south of Val-d'Or, Quebec. *Tectonophysics* **157**, 221-239.

Jacobson, C. E. 1997. Metamorphic convergence of upper and lower plates of the Vincent thrust, San Gabriel Mountains, southern California. *J. metamorph. Geol.*(In press).

Jacobson C. E. 1995. Qualitative thermobarometry of inverted metamorphism in the Pelona and Rand Schist, southern California, using calciferous amphibole in mafic schist. *J. metamorph. Geol.* **13**, 79-92.

Jacobson, C. E. 1990. The 40Ar/39Ar geochronology of the Pelona Schist and related rocks, southern California. *J. geophys. Res.* **95**, 509-528.

Jacobson, C. E., Dawson, M. R. & Postlethwaite, C. E. 1988. Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California. In: *Metamorphism and crustal evolution of the western United States* (edited by Ernst, W. G.), Prentice Hall, New Jersey, 976-997.

Jacobson, C. E., Dawson, M. R., & Postlethwaite, C. E. 1987. Evidence for the late-stage normal slip on the Orocopia Thrust and implications for the Vincent-Chocolate Mountains thrust problem. *Abs. with Progr. geol. Soc. Am.* **19**, 714.

Jacobson, C. E. & Dawson, M. R. 1995. Structural and metamorphic evolution of the Orocopia Schist and related rocks, southern California: Evidence for late movement on the Orocopia Fault. *Tectonics* **14**, 933-944.

Kleemann, U. & Reinhardt, J. 1994. Garnet-biotite thermometry revisited: the effect of Al VI and Ti in biotite. *Eur. J. Mineral.* **6**, 925-941.

Kohn, M. J. & Spear, F. S. 1990. Two new geobarometers for garnet amphibolites. with applications to southeastern Vermont. *Am. Mineral.* **75**, 89-96.

Krogh, E. J., Oh, C. W., Liou, J. G. 1994. Polyphase and anticlockwise P-T evolution for Franciscan eclogites and blueschist from Jenner, California, USA. *J. metamorph. Geol.* **12**, 121-134.

Laird, J. 1980. Phase equilibria in mafic schist from Vermont. *J. Petrol.* **21**. 1-37.

Laird, J. & Albee, A. L. 1981 Pressure, temperature, and time indicators in mafic schists - Their application to reconstructing the polymetamorphic history of Vermont. *Am J. Sci.* **281**, 127-175.

Laird. J., Lamphere, M. A. & Albee, A. L. 1984. Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schist from northern Vermont. *Am J. Sci.* **284**, 376-413.

Leake. B. E. 1978. Nomenclature of amphiboles. *Mineral. Mag.* **2**. 533-563.

Leake, B. E. 1965. The relationship between composition of calciferous amphibole and grade of metamorphism. In: *Controls of Metamorphism* (edited by Pitcher. W. S. & Flinn, G. W.), John Wiley & Sons. Inc.. New York. 299-318.

Lister. G. S. & Snoke, A.. W. 1984. S-C mylonites. *J. Struct. Geol.* **6**. 617-638.

Massone. H. J. & Schreyer. W. 1987. Phengite geobarometry based on the limiting assemblage with K-feldspar. phlogopite. and quartz. *Contr. Miner. Petrol.* **96**. 212-224.

Miyashiro, A. 1973. *Metamorphism and Metamorphic Belts.* Wiley. New York. 492 pp.

Oyarzabal. F. R.. Jacobson. C. E. & Haxel, G. B. 1997. The Chocolate Mountains fault in the Gavilan Hills area of southeastern California: Evidence of extensional reactivation and implications for the tectonic setting of the Orocopia Schist. Submitted to *J. Struct. Geol.*

Oyarzabal, F. R., Jacobson, C. E. & Haxel, G. B. 1995. The Chocolate Mountains Fault in the Gavilan Hills of southeasternmost California: an exhumation related normal fault. *Abs. with Progr. geol. Soc. Am.* **27**, A286.

Papike, J. J., Cameron, K. L. & Baldwin, K. 1974. Amphiboles and pyroxenes. characteristics of other than quadrilateral components and estimates of ferric iron from microprobe data. *Abs. with Progr. geol. Soc. Am.* **6**, 1053-1054.

Perchuk, L. L. & Lavrent'eva, I. V. 1983. Experimental investigation of exchange equilibria in the system cordierite-garnet-biotite. In: *Kinetics and Equilibrium in Mineral Reactions* (edited by Saxena, S. K.), *Adv. Phys. Geochem.* **3**, 199-239 Springer. New York.

Pigage, L. C. & Greenwood, H. J. 1982. Internally consistent estimates of pressure and temperature: the staurolite problem. *Am J. Sci.* **282**, 943-969.

Postlethwaite, C. E., & Jacobson, C. E. 1987. Early history and reactivation of the Rand Thrust, southern California. *J. Struct. Geol.* **9**, 195-205.

Powell R. & Evans J. A. 1983. A new geobarometer for the assemblage biotite-muscovite-chlorite-quartz. *J. metamorph. Geol.* **1**, 331-336.

Simpson. C. 1990. Microstructural evidence for northeastward movement on the Chocolate Mountain fault zone, southeastern California. *J. geophys. Res.* **95**. 529-537.

Simpson, C. & Schmid. S. M. 1983. An evaluation of criteria to determine the sense of movement in sheared rocks. *Bull. geol. Soc. Amer.* **94**. 1281-1288.

Vedder. J. G., Howell, D. G. & McLean, H. 1983. Stratigraphy. sedimentation. and tectonic accretion of exotic terranes. southern Coast Ranges. California. In: *Studies in Continental Margin Geology* (edited by Watkins. J. S. & Drake. C. L.). *Mem. Am. Ass. Petrol. Geol.* **34**. 471-496.

Velde. B. 1967. Si+4 content of natural phengites. *Contr. Miner. Petrol.* **14**. 250-258.

Velde. B. 1965. Phengite micas: synthesis. stability, and natural occurrence. *Am J. Sci.*. **263** 886-913.

Williams. M. & Grambling. J. 1990. Manganese, ferric iron. and the equilibrium between garnet and biotite. *Am. Mineral.* **75**, 886-908.

Wyllie, P. J. 1983. Experimental studies on biotite- and muscovite-granites and some crustal magmatic sources. In Migmatite, melting and metamorphism, (edited by Atherton, M.P. & Gribble, C.D.) Shiva Geology Series, 12-26.

Yeats, R. S. 1968. Southern California structure, seafloor spreading, and history of the Pacific Basin. *Bull. geol. Soc. Am.* **79**, 1693-1702.

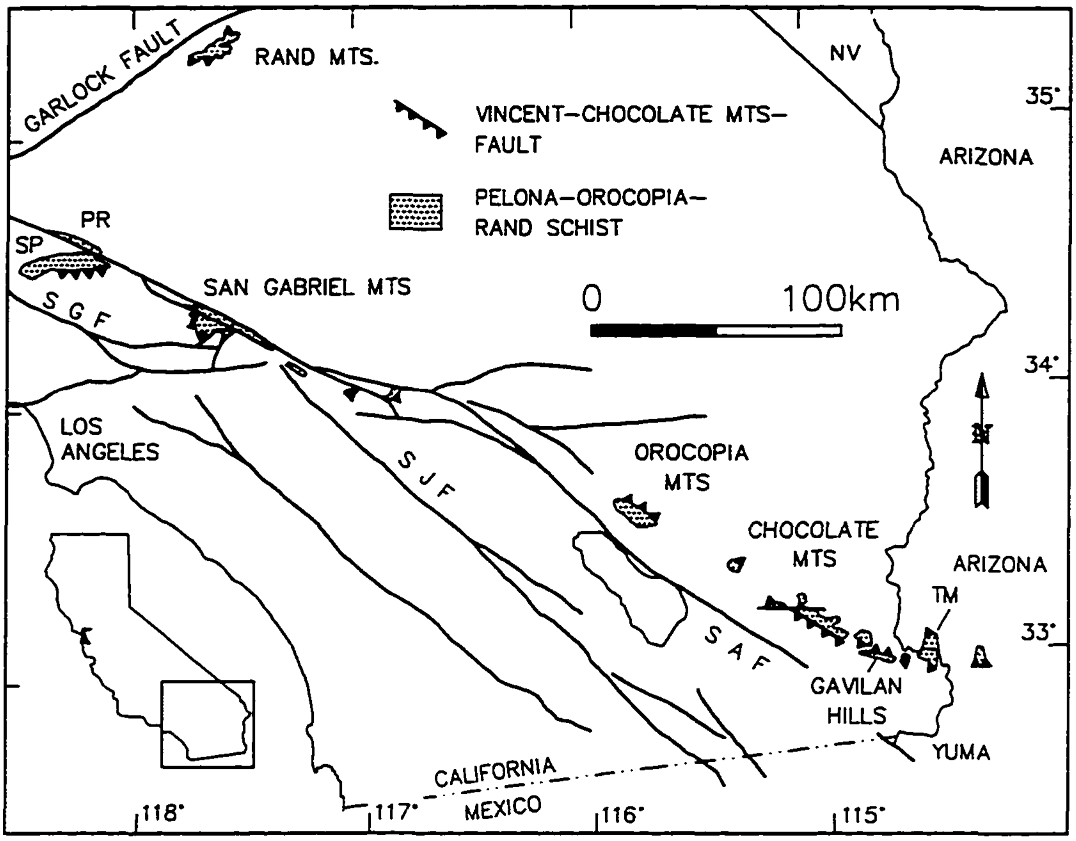

Figure 1. Distribution of the Pelona-Orocopia-Rand schist and Vincent-Orocopia-Chocolate Mountains fault in southern California. Additional occurrences of the schist are located to the northwest and southeast. The figure follows convention by using barbs to ornament the faults. However, many of the structures have probably been reactivated as normal faults. PR, Portal Ridge; SP, Sierra Pelona; SAF, San Andreas Fault; SGF, San Gabriel Fault; SJF, San Jacinto Fault; TM, Trigo Mountains.

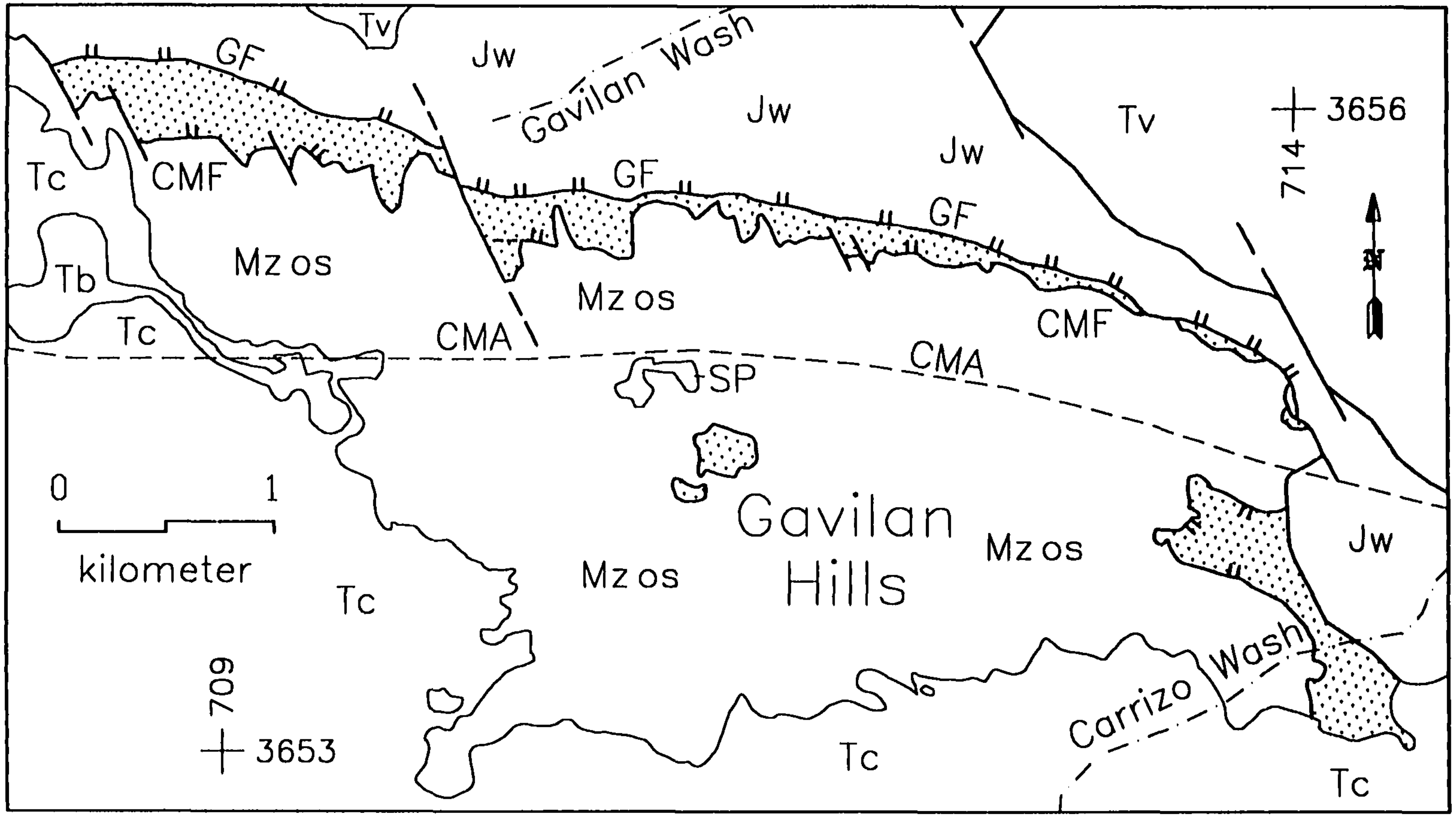

Figure 2. Geologic map of the Gavilan Hills. Dashed line shows the trace of the Chocolate Mountains anticlinorium. Dotted pattern, upper plate rocks. CMF, Chocolate Mountains fault; GF, Gatuna fault; Jw, Winterhaven Formation; Mz os, Orocopia Schist; SP, serpentinite; Tb, basalt (Miocene); Tc, conglomerate (Miocene & Pliocene); Tv, Quechan Volcanics. Contacts after Haxel (1977) and this study. Crosses indicates Universal Transverse Mercator (UTM) grid.

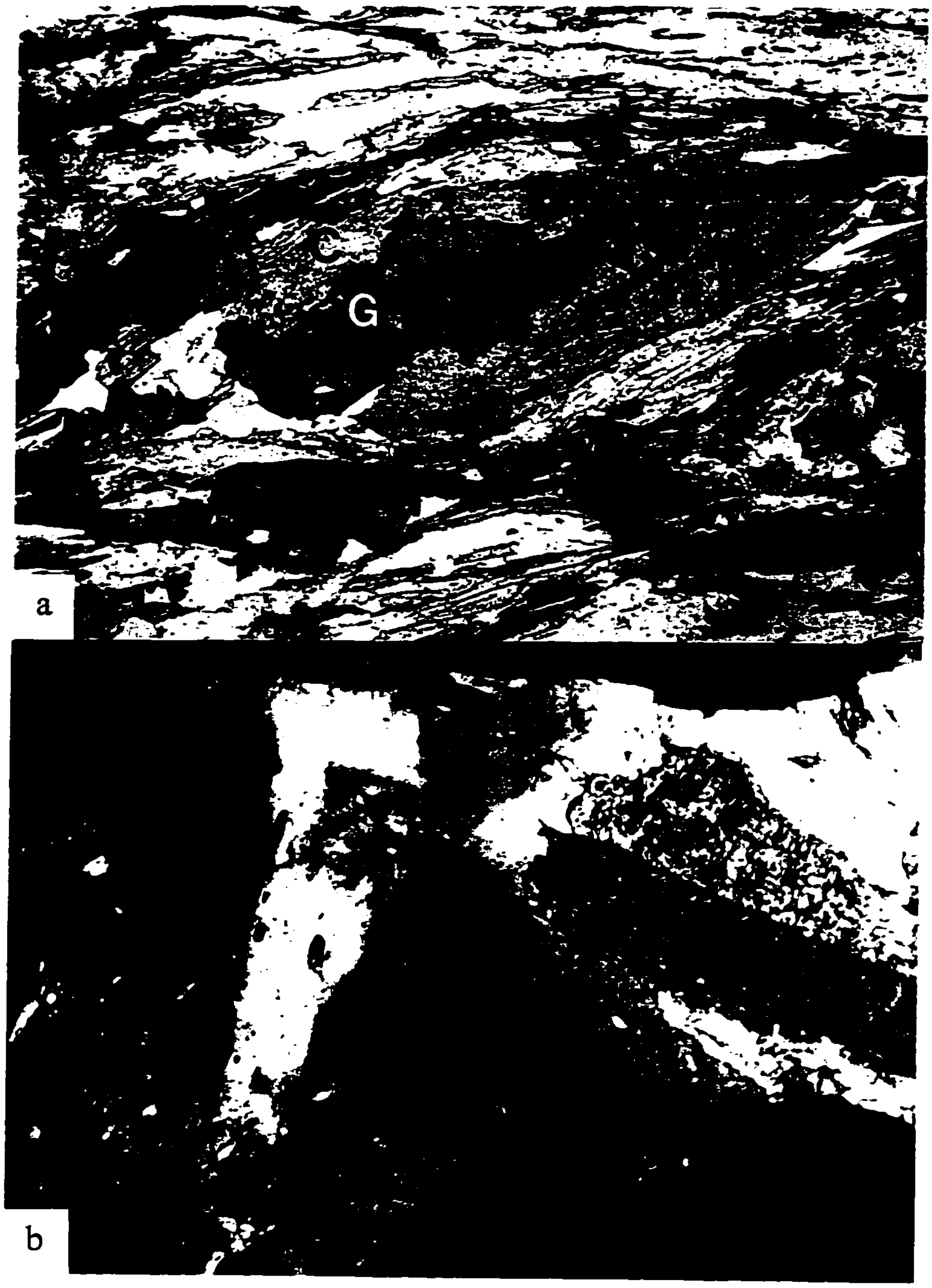

Figure 3. (a) Metagraywacke showing partial replacement of garnet (G) by chlorite (C). Width of field is 2.7 mm. Light is plane polarized. (b) Oligoclase (dark gray) rimmed by albite (light gray). Orocopia Schist. Width of field is 1.1 mm. Light is cross polarized.

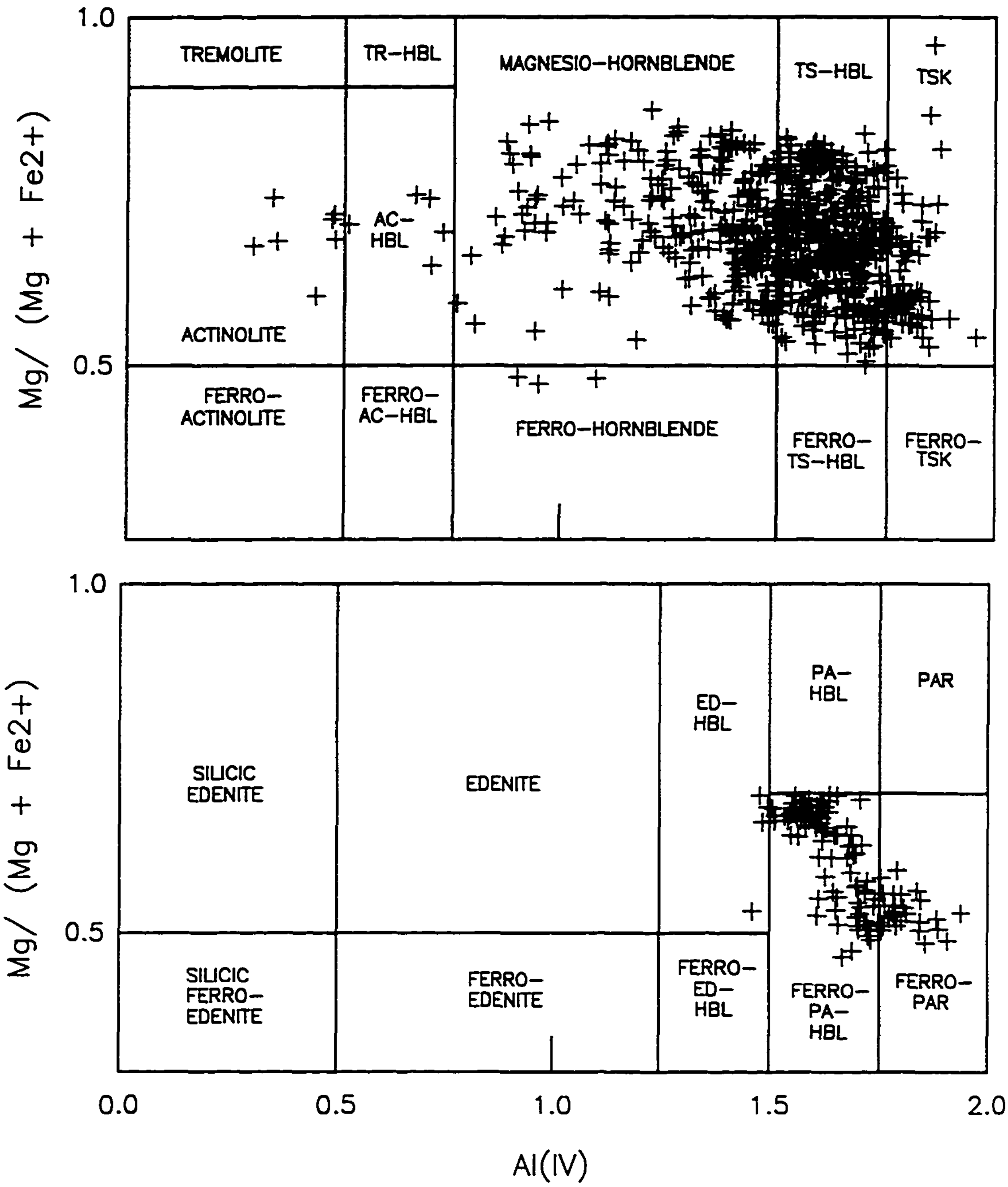

Figure 4. Amphibole compositions of mafic Orocopia Schist plotted on the classification diagrams of Leake (1978). AC, actinolitic; ED, edenitic; HBL, Hornblende; PA, pargasitic; PAR, Pargasite; TR, tremolitic; TS, Tschermakitic; TSK, Tschermakite.

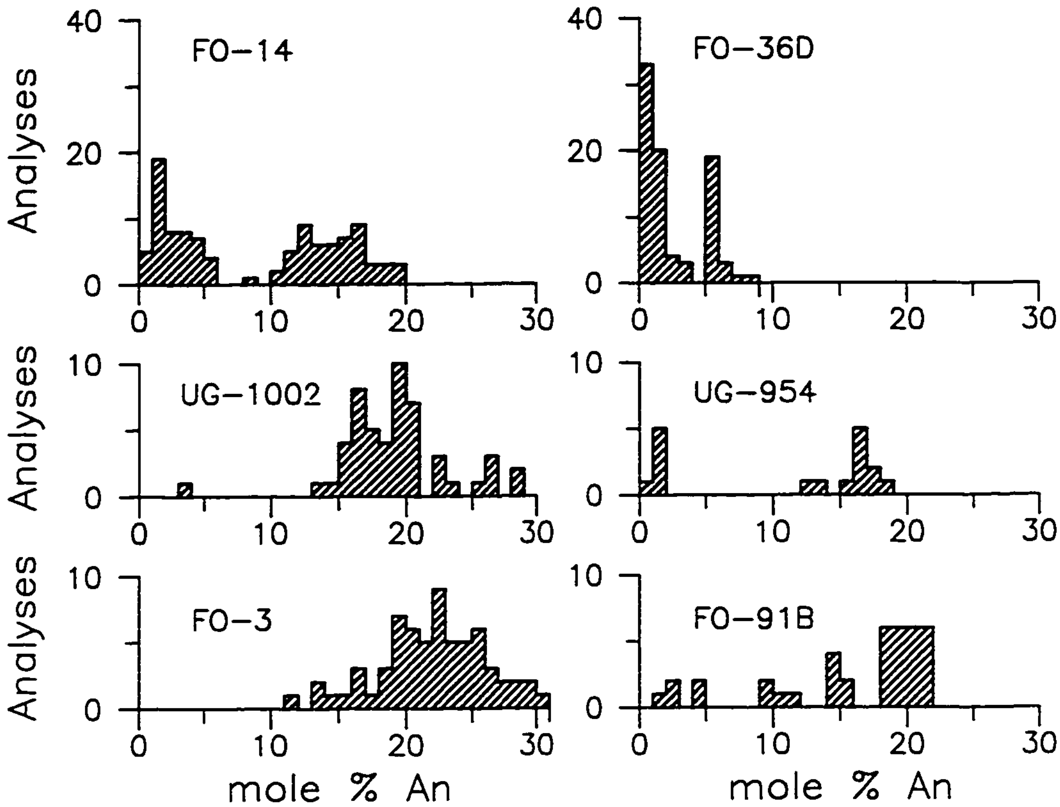

Figure 5. Plagioclase compositions for representative mafic Orocopia Schist samples.

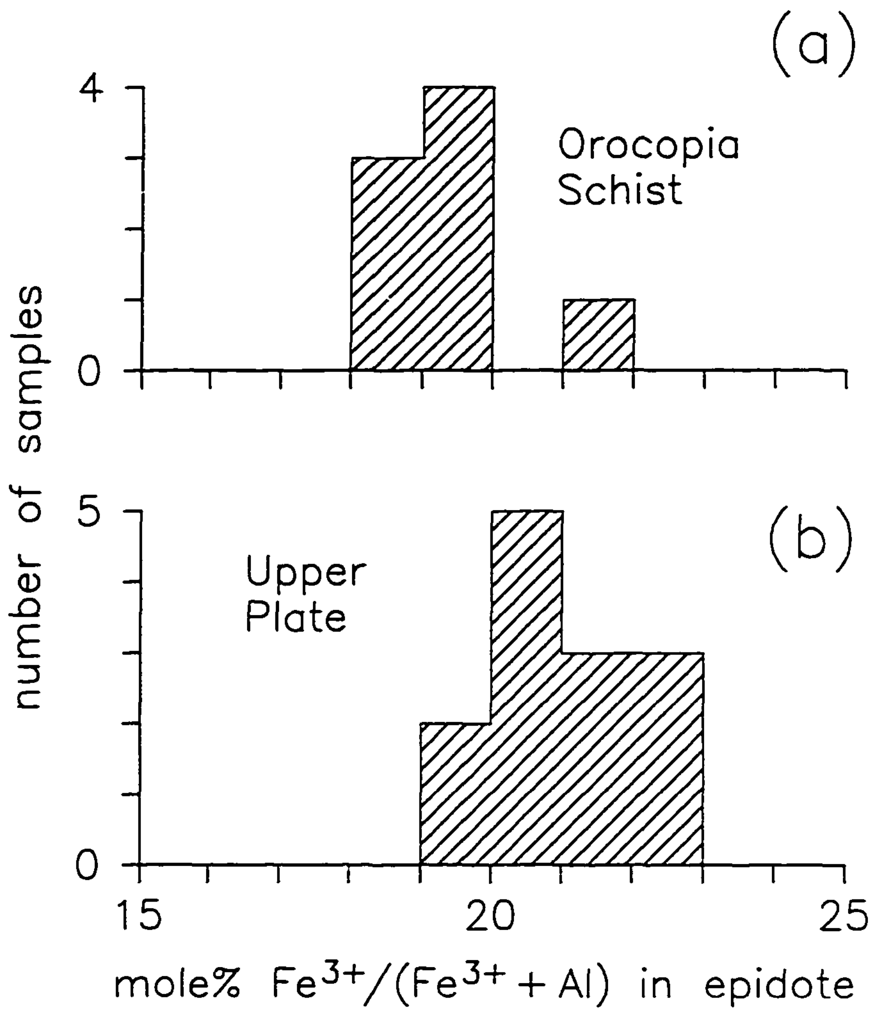

Figure 6. Average epidote composition for samples of (a) Orocopia Schist and (b) upper plate amphibolites.

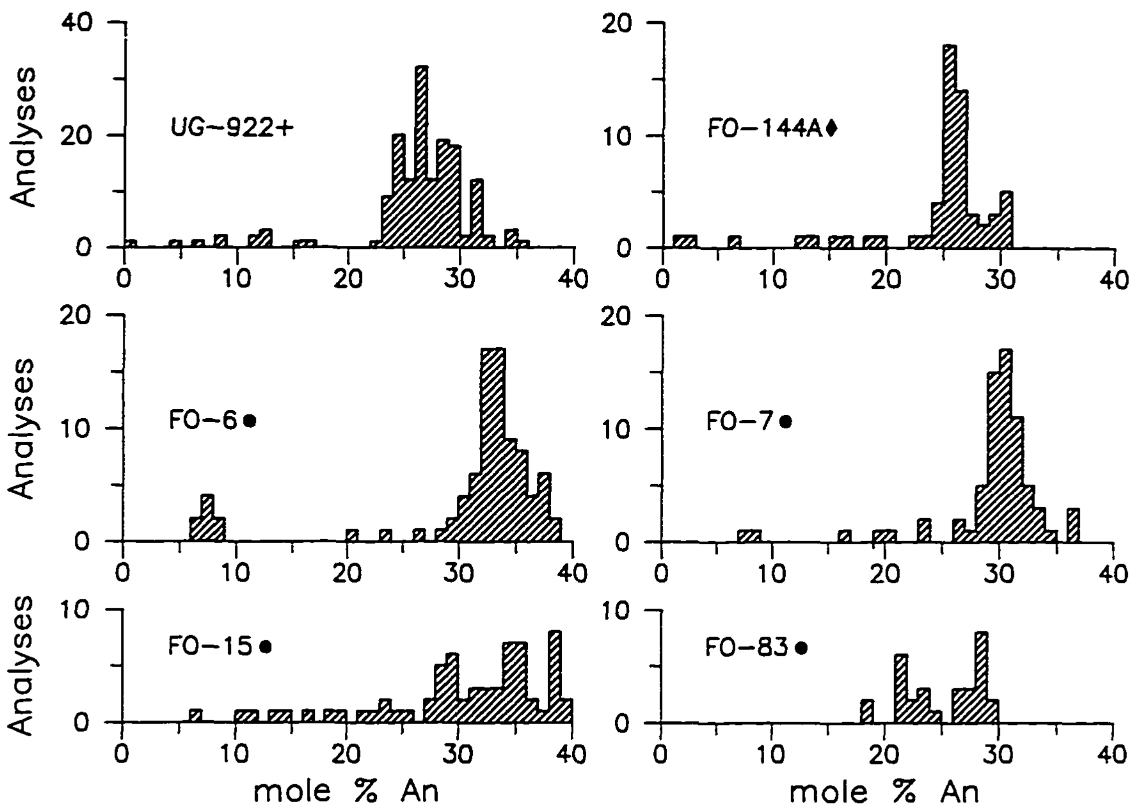

Figure 7. Plagioclase compositions for representative upper-plate samples.
• Amphibolite; ♦ amphibolitic gneiss; + felsic gneiss.

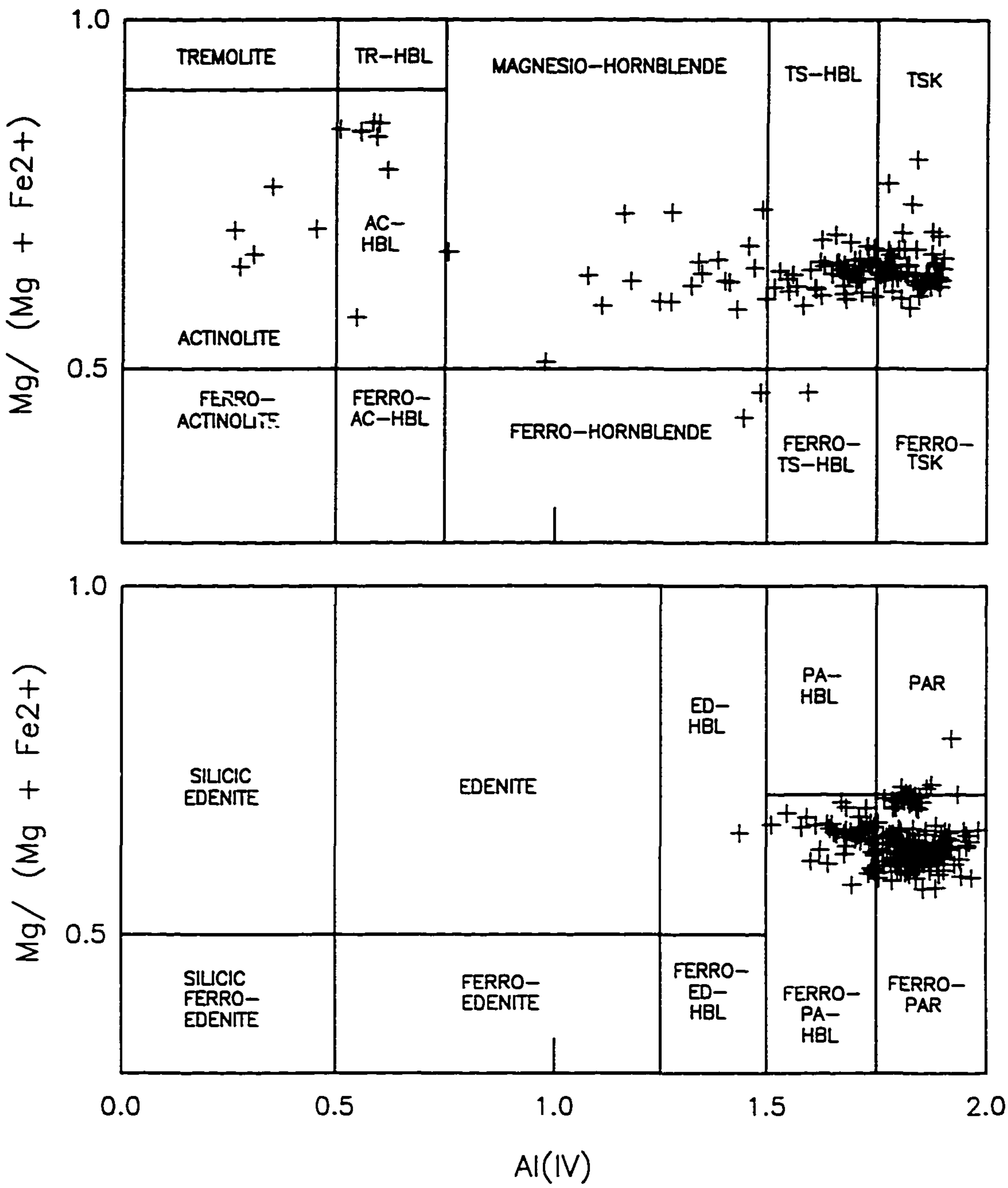

Figure 8. Amphibole compositions of upper-plate samples plotted on the classification diagrams of Leake (1978). Abbreviations as in Fig. 4.

Figure 9. (a) Hornblende grain (yellow) partially replaced by actinolite (blue to red), upper-plate amphibolite. Light is cross polarized. Width of field is 1.1 mm. (b) Replacement of garnet (G) by chlorite (C), upper-plate gneiss. Light is plane polarized. Width of field is 0.7 mm.

Figure 10. (a) Garnet grain (pink) being replaced by chlorite (light green), upper-plate gneiss. Light is plane polarized. (b) Upper-plate gneiss showing plagioclase grain (P) being replaced by sericite and saussurite. To the left, grains of biotite show partial replacement by chlorite. Light is cross polarized. Width of field is 2.7 mm for both microphotographs.

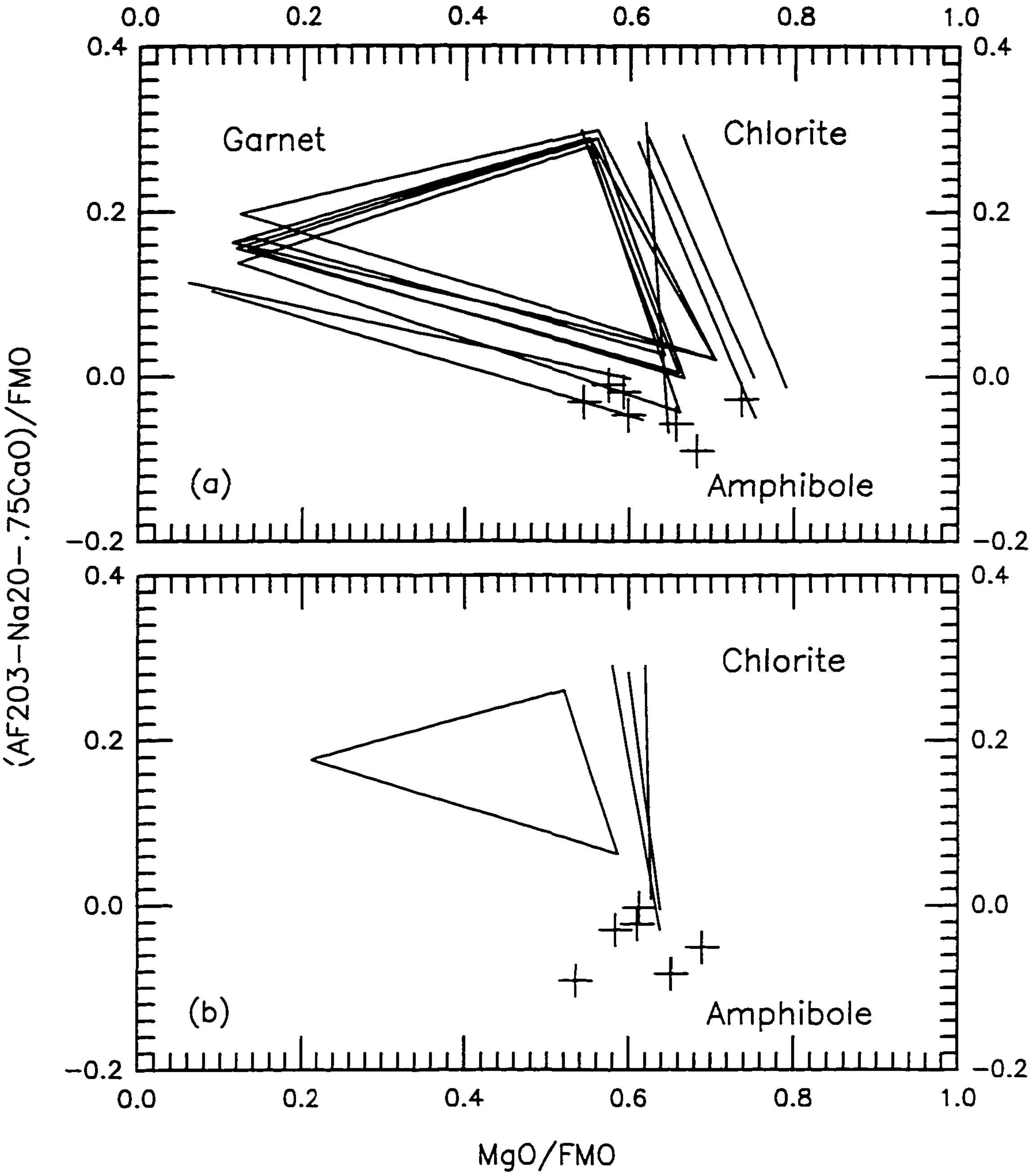

Figure 11. Epidote-albite projections (cf. Laird, 1980) for (a) mafic Orocopia Schist and (b) upper-plate amphibolites. Projecting phases are albite, epidote, quartz, and fluid. $AF_2O_3 = Al_2O_3 + Fe_2O_3$, $FMO = FeO + MgO + MnO$.

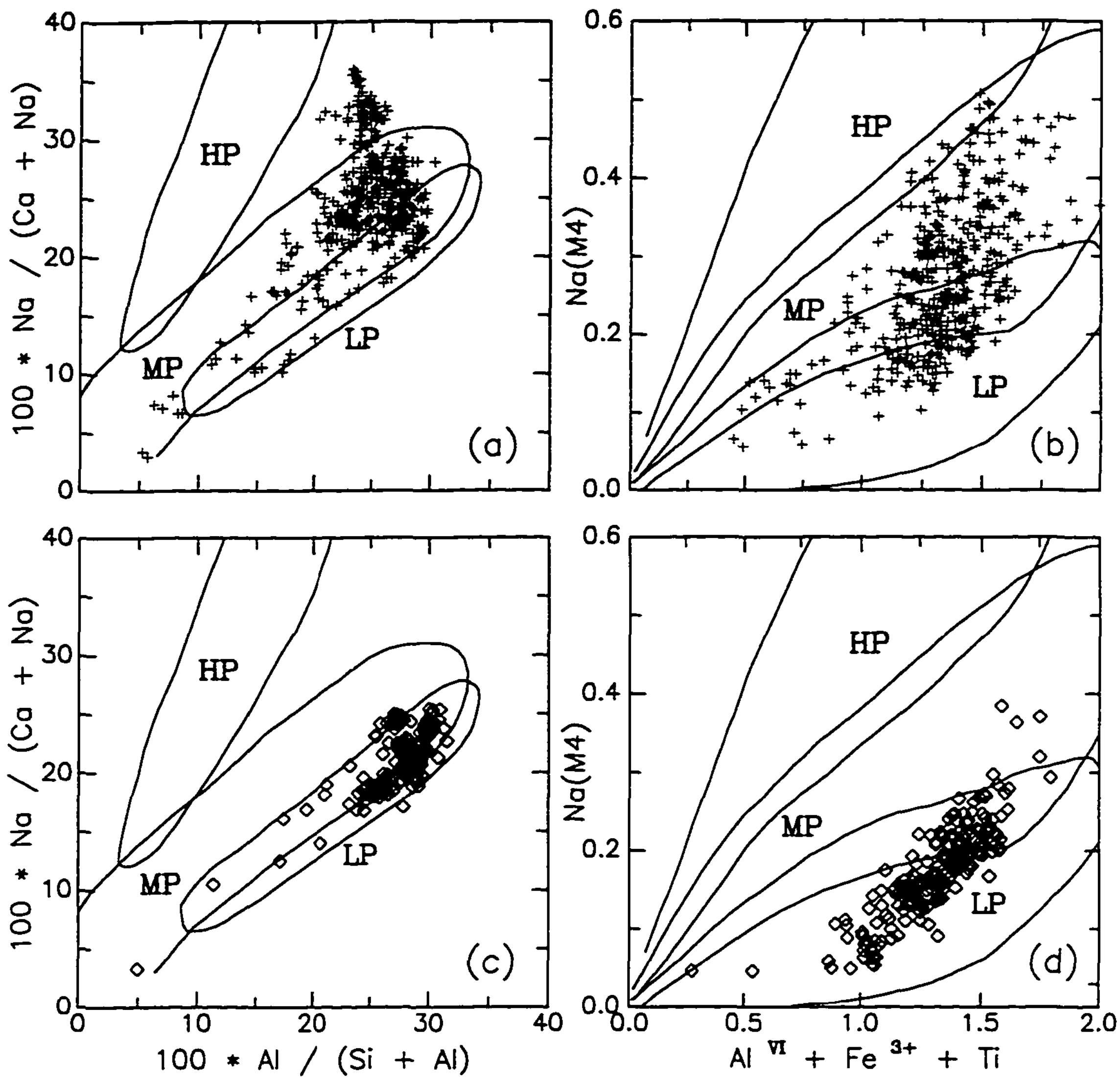

Figure 12. Some compositional parameters of calciferous amphibole. (a) & (b) Orocopia Schist, (c) & (d) upper-plate samples. Fields for (a) & (c) are visual fit to the data of Figs. 9-11 in Laird & Albee (1981). Fields for (b) & (d) are from Laird *et. al* (1984). Plots on the right side have been corrected for ferric iron. Plots on the right side of figure are independent of the method used to estimate ferric iron. HP, intermediate high- and high-pressure facies series; MP, medium-pressure facies series; LP, low-pressure facies series.

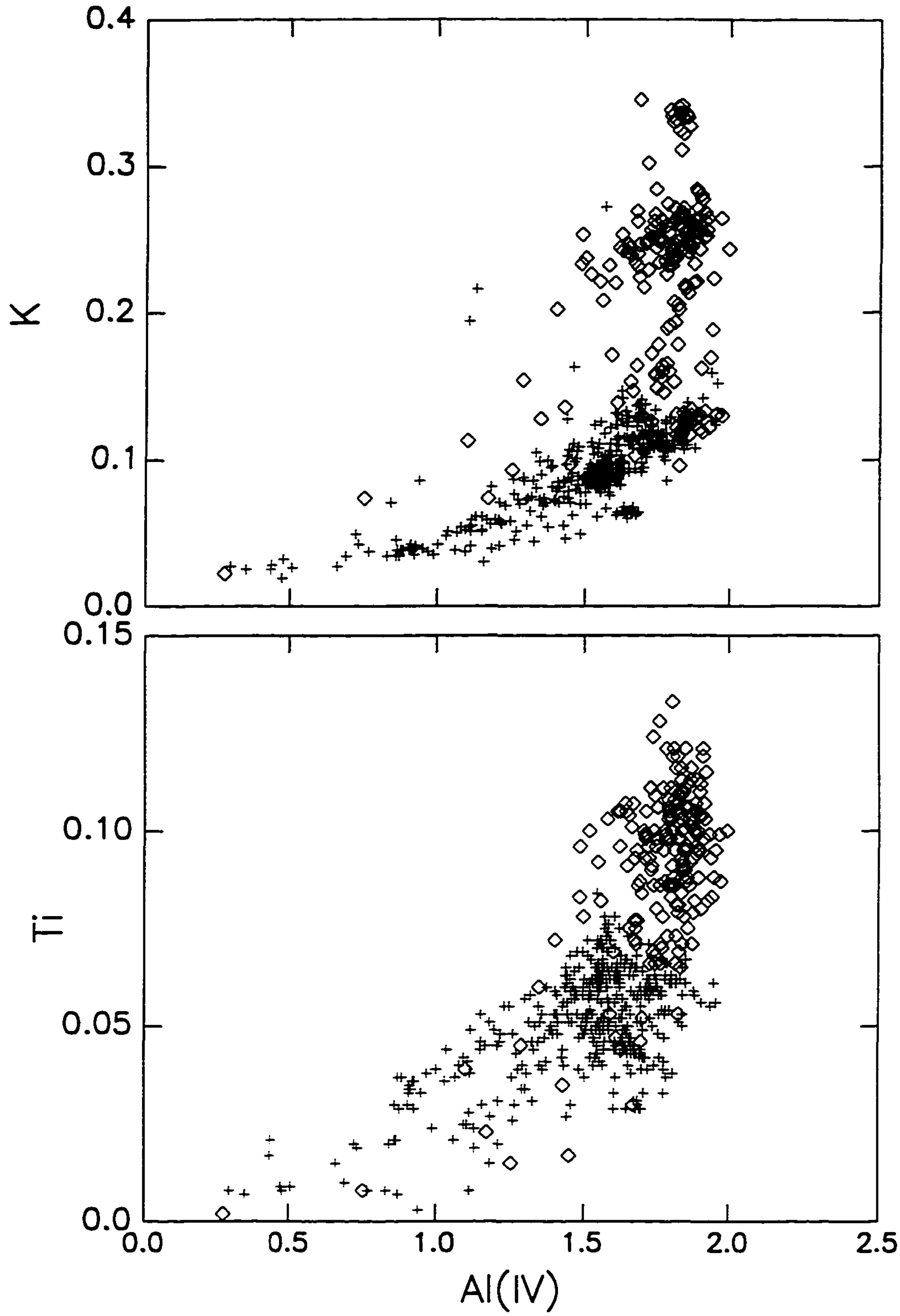

Figure 13. Variation of K and Ti versus tetrahedral Al in calciferous amphibole for Orocopia Schist and upper-plate rocks. Crosses. Orocopia Schist; open diamonds, upper plate.

Figure 14. (a) Prograde garnet-biotite association, Orocopia Schist. Width of field is 1.1 mm. (b) Prograde garnet-hornblende association, mafic Orocopia Schist. Width of field is 2.7 mm. Ligth is plane polarized in both microphotographs.

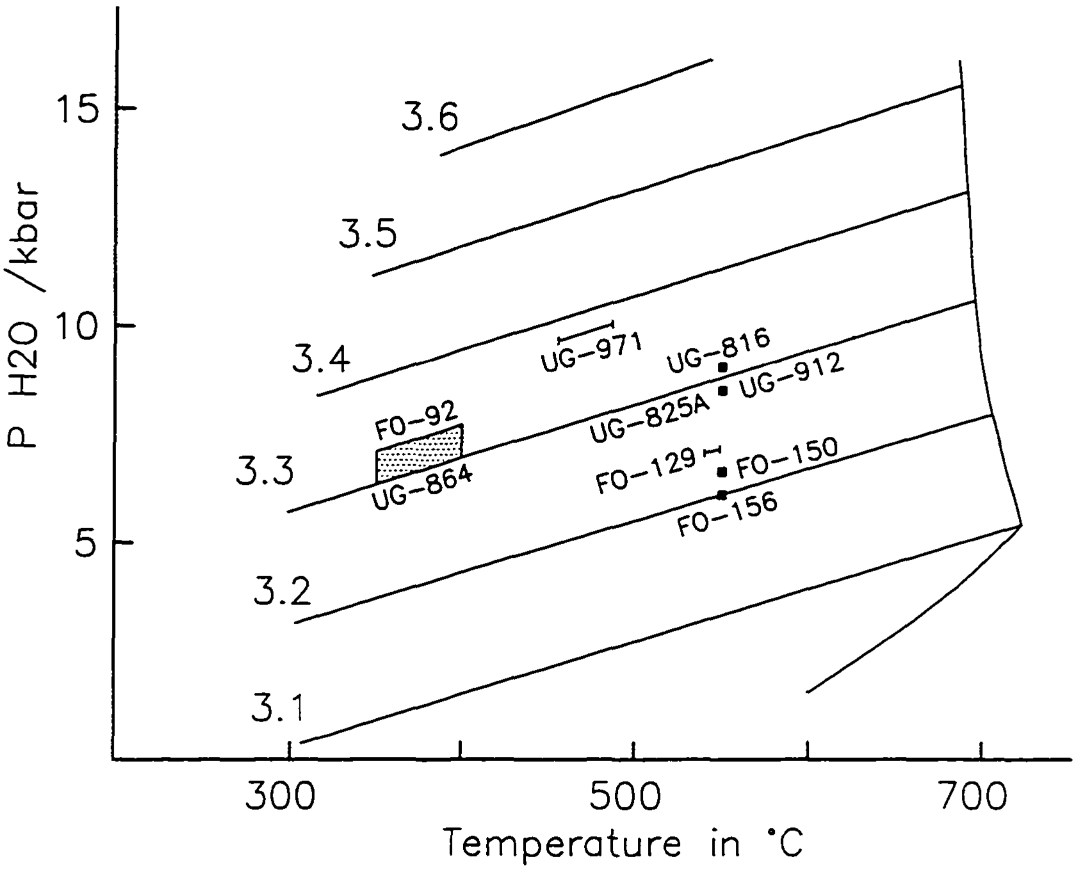

Figure 15. Isopleths of Si content per formula unit in phengite (Massone & Schreyer 1987). Bracketed lines are garnet-biotite temperatures (range from calibration 6 of table 2). Squares are samples with estimated temperatures of 550 °C. Dotted field represents upper plate samples (FO-92 & UG-864) at estimated temperature of 350 to 400° C.

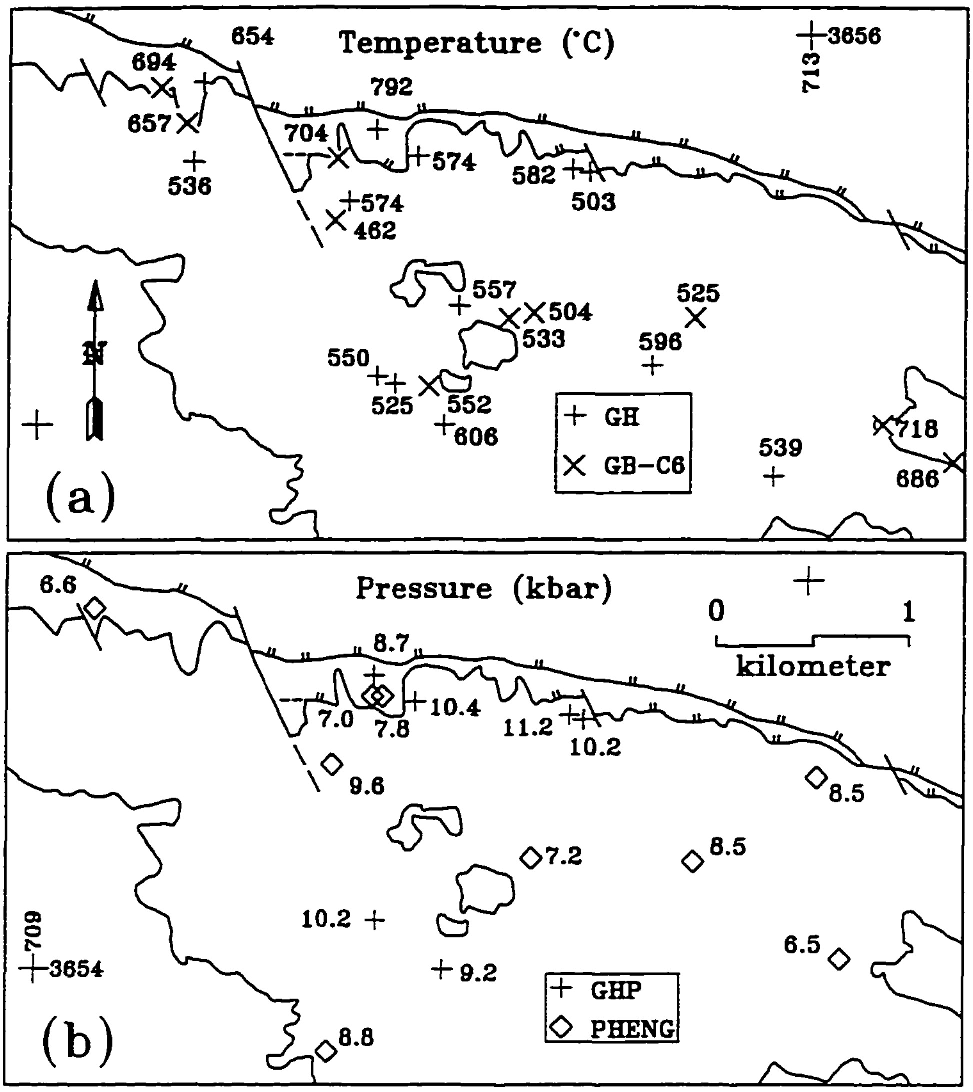

Figure 16. (a) Temperature estimates of Orocopia Schist and upper plate: **GH**, garnet-hornblende (Graham & Powell, 1984); **GB-C6**, garnet-biotite calibration 6 of table 2; (Kleemann & Reinhardt 1994). (b) Pressure estimates of Orocopia Schist and upper plate: **GHP**, garnet-hornblende-plagioclase (Kohn & Spear, 1990); **PHENG**, phengite barometer (Massone & Schreyer, 1987).

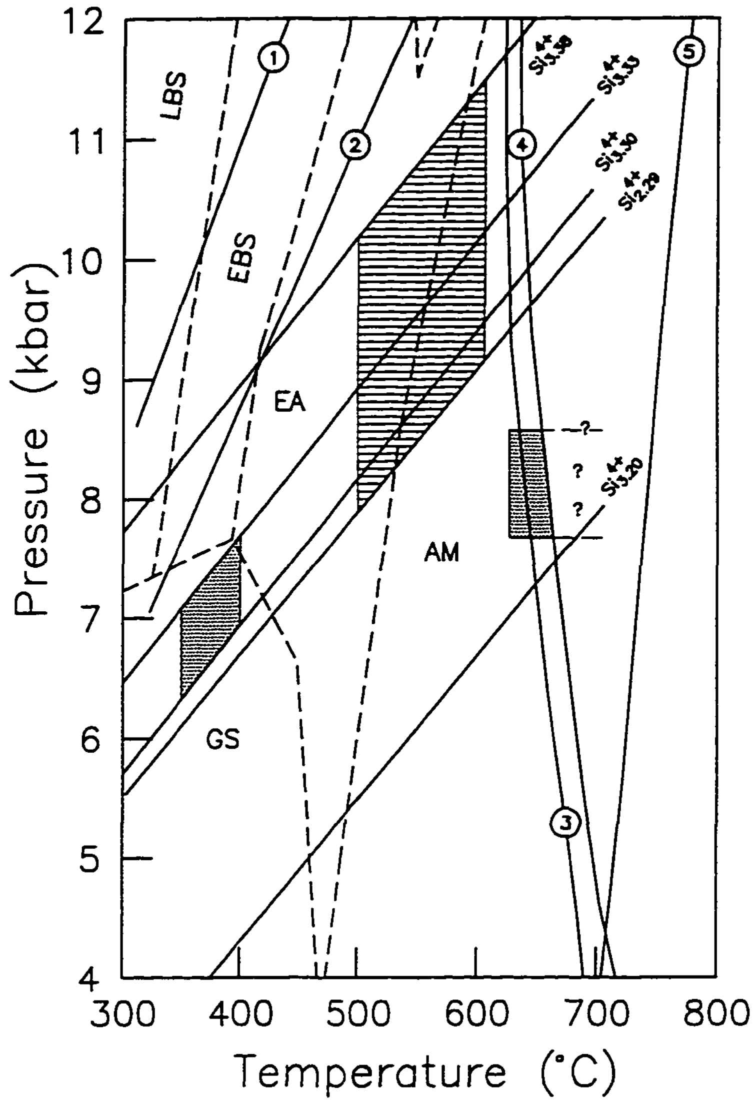

Figure 17. P-T diagram showing field of temperature and pressure for the thermometers and barometers used to infer conditions of metamorphism in the Orocopia Schist and upper plate rocks. Curves: (1) Albite ⇔ Jadeite + Quartz, (2) Albite ⇔ $Jadeite_{50}$ + Quartz (Holland 1980, 1983), (3) Tonalite solvus at 2% H2O content from Wyllie (1983), (4) begining of amphibolite melting with excess H_2O. (5) Initial breakdown of muscovite & biotite in the absence of vapor (Wyllie, 1983). Horizontally ruled area represent estimated P-T field for the Orocopia Schist. Dotted regions are P-T fields for the upper plate during prograde and retrograde metamorphism. Si isopleths for phengites are from Massone & Schreyer (1987). LBS, Lawsonite-blue schist facies; EBS, epidote-blueschist facies; EC, eclogite facies; EA, epidote-amphibolite facies; AM, amphibolite facies; GS, greenschist facies. Boundaries between metamorphic facies are shown in dashed lines (Krogh et al. 1994).

Table 1. Garnet rim compositions

	Metagraywacke					Gneiss				
Sample	FO-129	FO-194A	FO-246	UG-825A	UG-971	FO-85	FO-144A	FO-260	FO-262A	UG-922
SiO_2	37.98	37.87	37.77	37.75	37.74	37.53	38.39	37.89	37.62	37.22
TiO_2	0.08	0.05	0.10	0.20	0.10	0.00	0.00	0.00	0.00	0.01
Al_2O_3	20.97	21.20	21.17	21.43	21.55	20.95	20.95	22.03	21.73	20.89
FeO	24.00	25.35	29.18	16.54	26.39	25.06	24.26	31.89	31.16	22.48
MnO	2.02	1.60	1.18	5.19	2.35	3.64	3.89	1.71	2.14	4.86
MgO	0.61	1.40	1.70	0.75	0.69	2.95	2.61	4.36	3.71	2.52
CaO	13.47	11.48	9.70	18.10	12.09	10.03	10.84	2.80	4.56	11.25
Na_2O	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.01	0.00	0.00
K_2O	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.03
Total	99.13	98.95	100.82	99.97	100.67	100.15	100.93	100.69	100.90	99.26
Cations per 12 oxygens										
Si	3.03	3.02	2.99	2.97	2.97	2.97	3.01	2.98	2.97	2.97
Ti	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.97	1.99	1.97	1.98	2.01	1.95	1.93	2.04	2.02	1.96
Fe	1.60	1.69	1.93	1.08	1.75	1.66	1.59	2.10	2.05	1.50
Mn	0.13	0.10	0.07	0.34	0.15	0.24	0.25	0.11	0.14	0.32
Mg	0.07	0.16	0.20	0.08	0.08	0.34	0.30	0.51	0.43	0.30
Ca	1.15	0.98	0.82	1.52	1.02	0.85	0.91	0.23	0.38	0.96
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.54	0.57	0.64	0.36	0.58	0.53	0.52	0.71	0.68	0.49
Gr	0.39	0.33	0.27	0.50	0.34	0.27	0.30	0.08	0.13	0.31
Py	0.02	0.06	0.07	0.03	0.03	0.11	0.10	0.17	0.14	0.10
Sp	0.05	0.04	0.02	0.11	0.05	0.08	0.08	0.04	0.05	0.11

Table 1. (continuation)

Sample	Metagraywacke					Gneiss				
	FO-129	FO-194A	FO-246	UG-825A	UG-971	FO-85	FO-144A	FO-260	FO-262A	UG-922
SiO_2	36.75	36.72	36.51	36.58	37.24	35.82	35.66	36.36	36.38	35.59
TiO_2	2.06	1.60	1.68	1.41	1.84	2.32	2.07	1.54	16.62	2.53
Al_2O_3	15.69	16.42	17.16	16.16	15.92	16.25	16.02	16.73	1.65	15.66
FeO	24.16	19.85	18.99	21.85	21.24	20.47	20.71	20.92	19.95	21.15
MnO	0.30	0.35	0.12	0.27	0.34	0.19	0.21	0.13	0.17	0.24
MgO	7.56	10.11	11.20	9.86	9.26	10.46	10.62	10.99	11.28	10.01
CaO	0.02	0.02	0.00	0.05	0.04	0.10	0.02	0.01	0.01	0.03
Na_2O	0.06	0.07	0.05	0.05	0.60	0.10	0.12	0.08	0.04	0.14
K_2O	8.75	8.85	9.20	8.94	8.65	8.98	9.24	8.89	9.52	9.19
Total	95.35	93.99	94.91	95.17	95.13	94.69	94.67	95.65	95.62	94.54
Cations per 11 oxygens										
Si	2.85	2.83	2.78	2.81	2.86	2.76	2.75	2.77	2.77	2.76
Ti	0.12	0.09	0.09	0.08	0.10	0.13	0.12	0.08	0.09	0.14
Al	1.43	1.49	1.54	1.46	1.44	1.47	1.46	1.50	1.49	1.43
Fe	1.56	1.28	1.20	1.40	1.36	1.32	1.34	1.33	1.27	1.37
Mn	0.02	0.02	0.00	0.01	0.02	0.01	0.01	0.00	0.01	0.01
Mg	0.87	1.16	1.27	1.13	1.06	1.20	1.25	1.24	1.28	1.16
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.86	0.87	0.89	0.87	0.85	0.88	0.91	0.86	0.92	0.91
Na	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.02

Biotite average compositions.

Table2. Garnet-biotite temperatures (°C).

Calibration	1	2	3	4	5	6
Orocopia Schist						
FO-129*	386	469	512	549	535	504
FO-194A*	447	510	561	600	580	552
FO-246*	425	496	518	576	528	533
UG-825A*	430	499	596	464	652	525
UG-971*	330	429	437	493	452	462
Upper Plate						
FO-85+	688	646	792	772	822	704
FO-144A♦	650	627	762	746	798	686
FO-260+	745	674	778	666	754	694
FO-262A+	653	628	703	661	694	657
UG-922A+	701	652	818	790	866	718

1) Ferry & Spear (1978). 2) Perchuk & Lavrent'eva (1983). 3) Hodges & Spear (1982). 4) Ganguly & Saxena (1984) with activity coefficient of Ca in garnet based on a ternary subregular formulation. 5) Williams & Grambling (1990) with the parameters for their model 3. 6) Kleemann & Reinhardt (1994). All temperatures assuming a pressure of 8 kbars. Symbols: *, metagraywacke; +, tonalitic gneiss; ♦, amphibolitic gneiss.

Table 3. Garnet-hornblende thermometry (Graham & Powell 1984).

	XFEHB	XMGHB	XALM	XPY	XGR	XSP	T(° C)
Orocopia Schist							
FO-26	1.9858	2.4396	0.4990	0.0847	0.2899	0.1265	596
UG-103B	1.6433	2.3890	0.5702	0.0825	0.2744	0.0729	525
UG-217	2.3226	2.1152	0.5532	0.0435	0.3296	0.0736	539
UG-302	1.9089	2.4094	0.6329	0.0909	0.2564	0.0198	536
UG307	2.3814	1.9167	0.6292	0.0539	0.3030	0.0139	557
UG-869	2.0277	2.2990	0.5186	0.0564	0.3547	0.0703	574
UG-896	1.8330	2.3441	0.5750	0.0935	0.2925	0.0390	582
UG-954	1.8191	2.4193	0.5632	0.0797	0.2925	0.0646	550
UG-1002	1.8885	2.1961	0.5814	0.1022	0.2786	0.0378	606
UG-1049	2.1730	2.1188	0.6003	0.0395	0.3337	0.0265	503
UG-1092	1.9509	2.3107	0.5866	0.0821	0.3001	0.0311	574
Upper Plate							
FO-168	2.0702	2.0065	0.4927	0.1529	0.2797	0.0748	792
UG-925	1.9531	2.2356	0.5843	0.1647	0.2035	0.0475	654

All samples are amphibolites.

Table 4 Pressures estimates from garnet-hornblende-plagioclase. Khon and Spear (1990).

	XAn	XAb	XAlm	XPy	XGr	XSp	XFeHb	XMgHb	T(° C)	KD-FE	EqCt	P-Fe *	KD-MG	EqCt	P-Mg *
Orocopia Schist															
UG-896	0.156	0.841	0.575	0.094	0.292	0.039	0.220	0.281	550	25.810	8.003	11.4	3.283	2.925	11.2
UG-954	0.188	0.805	0.563	0.080	0.293	0.065	0.221	0.294	550	18.414	6.932	10.8	1.959	1.318	10.2
UG-1002	0.287	0.710	0.581	0.102	0.279	0.038	0.210	0.244	550	7.637	4.403	9.3	1.154	-0.211	9.2
UG-1049	0.164	0.834	0.600	0.039	0.334	0.027	0.277	0.270	550	29.720	8.178	11.5	2.004	1.352	10.2
UG-1092	0.186	0.810	0.587	0.082	0.300	0.031	0.244	0.289	550	18.830	7.002	10.8	2.226	1.733	10.4
Upper plate															
FO-168	0.597	0.396	0.493	0.153	0.280	0.075	0.232	0.224	650	2.123	0.977	8.0	0.680	-1.391	8.7

* Pressures in kbars. All samples are amphibolites.

GENERAL SUMMARY

The Chocolate Mountains fault in the Gavilan Hills was considered the original structure along which the oceanic Orocopia Schist was underplated beneath metamorphic and plutonic rocks of the continental U.S. This interpretation was based on evidence of NE transport of the upper plate and the understanding that a concordance in metamorphic conditions existed between both lithologic units along the fault. This study shows that the area has a complex deformational history and confirms the observation of Simpson (1990) that the structures along the Chocolate Mountains fault formed during retrograde metamorphism. A deformation zone localized at top of the Orocopia Schist contains two distinctive penetrative lineations and several generations of shear zones that are indicative of exhumation rather than subduction. An older lineation trends NNE and is present at all structural levels in most of the area. A younger lineation trends ENE to EW and is restricted to a narrow zone adjacent to the Chocolate Mountains fault on the northern and eastern flanks of the antiform. The shear zones can be divided into two different types. Type I shear zones record early stages of exhumation and formed in a ductile regime associated with low angle-normal faulting and retrogression of the mineral assemblage in both the Orocopia Schist and upper-plate rocks. During this episode of extension, the schist and upper plate were brought to middle crustal levels probably as a response to underplating and tectonic thickening of the Orocopia Schist. As deformation progressed, moderately to steeply dipping type II shear zones and associated mylonites accommodated were originated. Overprinting of ductile by brittle structures becomes more widespread especially near the top of the upper plate, suggesting that at this stage deformation was transferred to the Gatuna fault. At that time, the Orocopia Schist and upper plate became welded together and behaved as a coherent unit. The age of this first episode of extension is early Tertiary based on the available radiometric data. Exposure of the schist occurred during final unroofing of the area, probably during middle to late Tertiary time.

Differences in metamorphic temperature and pressure between the Orocopia Schist and upper plate indicate the reactivated character of the fault. Amphibole compositional parameters in the mafic schist and amphiboles of the upper plate show different trends between both lithologic units, as previously suggested by structural data. The Orocopia Schist belong to a higher-pressure series than the upper plate whereas amphibole in the upper plate originated at higher temperatures. Garnet-hornblende thermometry indicates temperatures of about 550°C for the Orocopia Schist, similar to garnet-biotite temperatures obtained with the geothermometer of Kleemann and Reinhardt (1994). Upper plate garnet-biotite temperatures are more variable, but are all higher than temperatures in the schist using similar calibrations. Accepted temperatures estimate for upper plate range from 600 and 650°C. Estimation of pressure in the Orocopia Schist using the phengite barometer of Massone and Schreyer (1987) and the hornblende-garnet-plagioclase geobarometer of Khon & Spear (1990) indicates pressures between 7.2 and 9.6 kbars. These pressures are comparable to geobarometric estimations on other bodies of POR schist.

Estimation of P-T conditions for the Orocopia Schist and upper plate rocks from the Gavilan Hills area show a gap in metamorphic conditions across the Chocolate Mountain fault, suggesting that part of the section is missing, and that the present contact between those two units is a reactivated post-metamorphic fault. Those findings are in agreement with structural data that show that parts of the contact are located along N-dipping shear zones, and that NE-vergent structures were probably produced during extensional reactivation of the fault. Confirmation of reactivation along the Chocolate Mountains fault and evidence of late origin for the structures with NE vergence remove the necessity for a collisional model to explain the origin of the POR schist. The POR schist has been considered a lateral equivalent of the Franciscan complex based on lithological similarities. Those similarities are very significant and lead us to conclude that the most probable tectonic setting for the origin of the POR schist is an Andean-type continental margin.

Further studies to characterized the relationships between the brittle history of the Chocolate Mountains fault and the Gatuna fault and Winterhaven Formation have been undertaken by Carl Jacobson and Matt Stamp, indicating that the latter was also active in early Tertiary time. Future work in the Tertiary volcanic and sedimentary sequence will help to understand the role of the Gatuna fault along the extensional history of the region and probably will allow to establish which structure and mechanism was responsible for the final unroofing of the area.

REFERENCES

Barth, A. P. 1988. Non-exotic terrane model for the Mesozoic San Gabriel terrane, southeasternmost California. *Abs. with Progr. geol. Soc. Am.* **20**, A275.

Bishop, K. M. & Ehlig, P. L. 1990. The Pelona fault, central Transverse Ranges, southern California: An extensional detachment fault?. *Abs. with Progr. geol. Soc. Am.* **22**, 8.

Bryant, B. & Reed, J. C. 1969. Significance of lineation and minor folds near major thrust faults in the southern Appalachians and Norwegian Calodonides. *Geol. Mag.* **106**, 412-429.

Burchfiel, B. C. & Davis, G. A. 1981. Mojave Desert and environs. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 217-252.

Crowell, J.C. 1968. Movement histories of faults in the Transverse Ranges and speculations on the tectonic history of California. *Stanford Univ. publ. geological Sciences* **11**, 323-341.

Crowell, J. 1981. An outline of the tectonic history of southeastern California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 583-600.

Dickinson, W. R. 1981. Plate tectonics and the continental margin of California. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 1-28.

Dillon, J.T., Haxel, G.B. & Tosdal, R.M. 1990. Structural evidence for northeastward movement on the Chocolate Mountains thrust, southeasternmost California. *J. geophys. Res.* **95**, 19,953-19,971.

Drobeck, P. A., Hillemeyer, F. L., Frost, E. G. & Liebler, G. S. 1986. The Picacho Mine: A gold mineralized detachment in southeastern California. *Ariz. geol. Soc. Dig.* **XVI**, 187-221.

Ehlig, P. 1958. Geology of the Mount Baldy region of the San Gabriel Mountains, California. Unpublished Ph. D. thesis, University of California, Los Angeles, California.

Ehlig, P. 1968. Causes and distribution of Pelona, Rand, and Orocopia Schist along the San Andreas and Garlock faults. *Stanford Univ. Publ. geol. Sci.* **11**, 294-305.

Ehlig, P. 1981. Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges. In: *The Geotectonic Development of California* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 253-283.

Escher, A. & Watterson, J. 1974. Stretching fabrics, folds, and crustal shortening. *Tectonophysiscs*, **22**,223-231.

Frost, E. G. & Martin, D. L. 1983. Overprint of Tertiary detachment deformation on the Mesozoic Orocopia Schist and Chocolate Mtns. thrust. *Abs. with Progr. geol. Soc. Am.* **15**, 557.

Goodmacher, J. L., Barnett, G., Ouachrif, L., Vidigal, A. & Frost, E. 1989. TheClemens Well fault in the Orocopia Schist and Chocolate Mtns. Thrust. *Abs. with Progr. geol. Soc. Am.* **15**, 557.

Graham, C. M. 1975. Inverted metamorphic zonation and mineralogy of the Pelona Schist. Sierra Pelona, Transverse Ranges. *Abs. with Progr. geol. Soc. Am.* **7**, 321-322.

Graham, C. M. & England, P. C. 1976. Thermal regimes and regional metamorphism in the vicinity of overthrust faults: An example of shear heating and inverted metamorphic zonation from southern California. *Earth Planet. Sci. Lett.* **31**, 142-152.

Hamilton, W. 1987. Crustal extension in the Basin and Range Province, southwestern United States. In: *Continental Extensional Tectonics* (edited by Coward, M. P., Dewey, J. F., & Hancock, P. L.), *Spec. Publs. geol. Soc. Lond.* **28**, 155-176.

Hamilton, W. 1988. Tectonic setting and variations with depth of some Cretaceous and Cenozoic structural and magmatic systems of the western United States. In: *Metamorphism and Crustal Evolution of the Western United States* (edited by Ernst, W. G), Prentice-Hall, Englewood Cliffs, New Jersey, 1-40.

Haxel, G. B. 1977. The Orocopia Schist and the Chocolate Mountain Thrust, Picacho-Peter Kane mountain area, southeasternmost Califonia. Unpublished Ph.D. thesis. University of California, Santa Barbara, California.

Haxel, G .B. & Dillon, J. T. 1978. The Pelona-Orocopia Schist and Vincent-Chocolate Mountains Thrust System, Southern California. In: *Mesozoic Paleogeography of the Western United States* (edited by Howell, D. J. & McDougall, K. A.), Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium **2**, 453-469.

Haxel, G. B. & Tosdal, R. M. 1986. Significance of the Orocopia Schist and Chocolate Mountains thrust in the late Mesozoic tectonic evolution of the southeastern California-southwestern Arizona region: extended abstract. In: *Frontiers in Geology and Ore Deposits of Arizona and the Southwest* (edited by Beatty, B. & Wilkinson, P. A. K.). *Ariz. geol. Soc. Dig.* **16**, 282-293.

Haxel, G. B., Tosdal, R. M. & Dillon, J. T. 1985. Tectonic Setting and lithology of the Winterhaven Formation: A new Mesozoic stratigraphic unit in southeasternmost California and southwestern Arizona. *Bull. U.S. geol Surv* **1599**, 1-19.

Jacobson, C. E. 1980. Deformation and metaorphismof the Pelona Schist beneath the Vincent thrust, San Gabriel Mountains, California, Unpublished Ph.D. thesis. University of California, Los Angeles, California.

Jacobson, C. E. 1983a. Relationship of deformation and metamorphism of the Pelona Schist to movement on the Vincent Thrust, San Gabriel Mountains, southern California. *Am. J. Sci.* **283**, 587-604.

Jacobson, C. E. 1983b. Structural geology of the Pelona Schist and Vincent thrust. San Gabriel Mountains, California. *Bull. geol. Soc Am.* **94**, 753-767.

Jacobson, C. E. 1983c. Complex refolding history of the Pelona, Orocopia, and Rand Schists, southern California. *Geology* **11**, 583-586.

Jacobson, C. E. 1984. Petrological evidence for the development of refolded folds during a single deformational event. *J. Struct. Geol.* **6**, 563-570.

Jacobson, C. E. 1990. The 40Ar/39Ar geochronology of the Pelona Schist and related rocks, southern California. *J. geophys. Res.* **95**, 509-528.

Jacobson C. E. 1995. Qualitative thermobarometry of inverted metamorphism in the Pelona and Rand Schist, southern California, using calciferous amphibole in mafic schist. *J. metamorph. Geol.* **13**, 79-92.

Jacobson, C. E. 1997. Metamorphic convergence of upper and lower plates of the Vincent thrust, San Gabriel Mountains, southern California. *J. metamorph. Geol.* (in review).

Jacobson, C. E. & Dawson, M. R. 1995. Structural and metamorphic evolution of the Orocopia Schist and related rocks, southern California: Evidence for late movement on the Orocopia Fault. *Tectonics* **14**, 933-944.

Jacobson, C. E., Dawson, M. R. & Potlethwaite, C. C. 1988. Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California. In: *Metamorphism and Crustal Evolution of the Western United States* (edited by Ernst, W. G.), Prentice-Hall, Englewood Cliffs, New Jersey, 976-997.

Jacobson C. E., Oyarzabal, F. R. & Haxel G. B. 1996. Subduction and exhumation of the Pelona-Orocopia-Rand schists, southern California. *Geology*, **24**, 547-550.

Jacobson, C. E. & Sorensen, S. S. 1986. Amphibole compositions and metamorphic history of the Rand Schist and the greenschist unit of the Catalina Schist, southern California. *Contr. Miner. Petrol.* **92**, 308-315.

Kleemann, U. & Reinhardt, J. 1994. Garnet-biotite thermometry revisited: the effect of Al VI and Ti in biotite. *Eur. J. Mineral.* **6**, 925-941.

Kohn, M. J. & Spear, F. S. 1990. Two new geobarometers for garnet amphibolites, with applications to southeastern Vermont. *Am. Mineral.* **75**, 89-96.

Massone, H. J. & Schreyer, W. 1987. Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz. *Contr. Miner. Petrol.* **96**, 212-224.

Miller, F. K. & Morton, D. M. 1980. Potassium-argon geochronology of the eastern Transverse Ranges and southern Mojave Desert, southern California. *Prof. pap. U.S. geol Surv* **1152**, 1-30.

Postlethwaite, Clay C., & Jacobson, Carl E.. 1987. Early history and reactivation of the Rand Thrust, southern California. *J. Struct. Geol.* **9**, 195-205.

Powell, R. 1981. Geology of thencrystalline basement complex, eastern Traverse Ranges, southern California: Constraints on regional tectonics interpretations. Unpublished Ph.D. Thesis. California Institute of Technology, Pasadena, California.

Richard, S. M. & Haxel, G. B. 1991. Progressive exhumation of the Orocopia and Pelona Schist along a composite normal fault system, southeastern California and southwestern Arizona. *Abs. with Progr. geol. Soc. Am.* **23**, 92.

Sharry, J. 1981. The Geology of the western Tehachapi Mountains, California. Unpublished Ph.D. thesis. Massachusetts Institute of Technology, Massachusetts.

Silver, L. T. & Nourse, J. A. 1986. The Rand Mountains Thrust Complex in comparison with the Vincent Thrust-Pelona Schist relationship, southern California. *Abs. with Progr. geol. Soc. Am.* **18** 185.

Simpson, C. 1986. Microstructural evidence for northeastward movement on the Vincent-Orocopia-Chocolate Mountains thrust system. *Abs. with Progr. geol. Soc. Am.* **18**, 185.

Simpson, C. 1990. Microstructural evidence for northeastward movement on the Chocolate Mountain fault zone, southeastern California. *J. geophys. Res.* **95**, 529-537.

Terres, R. R. & Luyendyk, B. P. 1985. Neogene tectonic rotation of the San Gabriel region, suggested by paleomagnetic vectors. *J. geophys. Res.* **90**, 12,467-12,484.

Vargo, J. M. 1972. Structural geology of a portion of the eastern Rand Mountains, Kern and San Bernardino Counties. Unpublished M.A. thesis. University of Southern California, Los Angeles, California.

Vedder, J.G., Howell, D.G. & McLean, Hugh 1983. Stratigraphy, sedimentation, and tectonic accretion of exotic terranes, southern Coast Ranges, California. In: *Studies in Continental Margin Geology* (edited by Watkins, J. S. & Drake, C. L.), *Mem. Am. Ass. Petrol. Geol.* **34**, 471-496.

Yeats, R.S., 1968. Southern California structure, seafloor spreading, and history of the Pacific Basin. *Bull. geol. Soc. Am.* **79**, 1693-1702.

ACKNOWLEDGMENTS

I want to express my gratitude to Dr. Carl Jacobson, who suggested this dissertation project and secured the funds for its completion. Carl has been a great mentor and a source of inspiration and wisdom. His help on the field and the in lab has been invaluable to my professional knowledge. I also want to extend my appreciation to Dr. Gordon Haxel for introducing me to the Gavilan Hills and for his valuable comments.

I have benefited at different times from discussions with Paul Spry. Gordon Haxel. Daniel May, Richard Tosdal, and Matt Stamp. Professors Kenneth Windom. John Sandor and Ladon Jones were part of my graduate committee and their assistance was much appreciated. My fellows graduate students Beth Johnson, Greg Caron, Barbara Berquam. Dean Lewis, Ran Chen, Jim Eidem, Matt Stamp, Walter Prexl. John Baldwin. Mike Weiss. Jill Rosemberg, Ronald Sarno, and Andrew Lee made my life at Iowa State enjoyable and I want to thank them for their support and help. My appreciation to Antonio and Emma Mallarino, Gustavo and Carlota Gutierrez, and Ricardo and Manuela Salvador for their support over the years. DeAnn Frisk was a great help with all kind of office problems and an excellent source of information.

Most of all, I am indebted to my parents, Sabas and Erminia Oyarzabal. my brothers. Emilio and Omar, my sister Noemi. and my nephews, Alejandro and Esteban. for their unconditional support and love.