Exhumation history of the Orocoipa Schist and related rocks in the Gavilan Hills area of southeasternmost California

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ABSTRACT

The Gavilan Hills area of southeasternmost California exposes three distinctly different crystalline rock packages in a postmetamorphic, E–W elongated dome. Structurally deepest is the relatively high-pressure, eugeoclinal Orocoipa Schist, which underlies the low-angle Chocolate Mountains fault. Above the schist are gneisses derived from mid- to lower-crustal levels of the Mesozoic Cordilleran magmatic arc. The gneisses, in turn, are separated by the Gatuna fault from low-grade metasedimentary and metavolcanic rocks of the Winterhaven Formation. The Chocolate Mountains fault was originally thought to be a SW-dipping subduction thrust along which an exotic continental sliver was sutured to North America. Recent workers, however, have proposed that it is a late fault responsible for exhumation of the Orocoipa Schist and that it places no constraints on burial history. The latter interpretation is supported by the presence in the schist of two distinct structural fabrics, an older one presumably related to underthrusting, and a younger one attributed to exhumation. The older fabric is preserved in schist away from the Chocolate Mountains fault and is associated with a NNE–SSW-trending lineation that formed during prograde metamorphism to lowermost amphibolite facies. The younger fabric is best developed within ~100 m structurally of the Chocolate Mountains fault and is characterized by discrete shear zones, greenschist-facies retrogression, and E–W-trending lineations. Lineations with similar orientation also occur in gneiss adjacent to both the Chocolate Mountains and Gatuna faults and in the Winterhaven Formation. This

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observation, combined with interpretation of outcrop patterns, suggests that the Ga-
tuna fault, which was previously considered a steep, shallow-level fault of Miocene
age, is a low-angle structure that accommodated relatively high-temperature defor-
mation similar to that recorded by the Chocolate Mountains fault. Both faults may
have been synchronously active. However, because the Gatuna fault exhibits more
intense brittle overprinting of early mylonitic fabrics and greater structural excision
than the Chocolate Mountains fault, it is indicated to have been more recently active
and the more important of the two in exhuming the schist and overriding gneiss to
shallow crustal levels.

Thermal history results based upon $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of hornblende, muscovite,
biotite, and K-feldspar and previous apatite fission track measurements reveal a two-
stage exhumation history that we relate to slip along the Chocolate Mountains and
Gatuna faults, respectively. An initial phase of rapid cooling occurred from $<60$ Ma
to $44$ Ma. Younger and more discordant $^{40}\text{Ar}/^{39}\text{Ar}$ ages recorded by hornblendes from
the schist ($52–57$ Ma) relative to the gneiss ($59–64$ Ma) confirm postpeak metamorphic
juxtaposition of the two units along the Chocolate Mountains fault in a manner con-
sistent with normal faulting. Coincidence of muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages between the
Orocopia Schist and gneiss implies that this juxtaposition occurred by $48 \pm 2$ Ma
and indicate that the Chocolate Mountains fault is a Laramide-age structure. Biotite
ages ranging from $45$ to $31$ Ma reveal that the initial exhumation phase was followed
by protracted residence of the schist and gneiss in the middle crust at $\sim 350$ °C. K-
feldspars record a second period of rapid exhumation from $28$ to $24$ Ma, which we
correlate with the brittle phase of movement on the Gatuna fault. This second phase
of exhumation is considered to reflect an early stage of the middle Tertiary extensional
event that is widespread in southeastern California and southwestern Arizona. Lo-
calized disruption of the Chocolate Mountains fault that juxtaposed structurally
deeper schist against gneiss at the eastern end of the Gavilan Hills probably also
occurred at this time.

INTRODUCTION

The Pelona, Orocopia, and Rand Schists of southern Cali-
ifornia and southwesternmost Arizona comprise a widely known
but poorly understood group of metamorphosed graywacke-
basalt-chert assemblages exposed beneath the low-angle
Vincent–Chocolate Mountains fault system (Fig. 1A). Origi-
nally interpreted as a Late Cretaceous–early Tertiary thrust zone,
the Vincent–Chocolate Mountains fault system is now consid-
ered to be a composite of burial and exhumation structures of
various ages (Haxel and Dillon, 1978; Ehlig, 1981; Frost et al.,
1982, 1989; Jacobson, 1983a, 1983b; Haxel et al., 1985; Silver
and Nourse, 1986; Postlethwaite and Jacobson, 1987; Malin et
al., 1995; Jacobson et al., 1988, 1996; Oyarzabal et al., 1997;
Wood and Saleeby, 1997). Prograde metamorphism of the
Pelona–Orocopia–Rand Schists occurred in Late Cretaceous–
early Tertiary time at depths of 25 to $>30$ km, shortly after
deposition of the graywacke (Jacobson, 1990; Grove et al.,
2000; Jacobson et al., 2000). Tectonic models for the schists
fall into three basic categories. Two of these involve low-angle,
est-dipping subduction of the Farallon plate related to the Lar-
amide orogeny. In one case, the schists are considered to be
part of the Franciscan subduction complex (Yeats, 1968; Crow-
Hamilton, 1987, 1988; Malin et al., 1995; Jacobson et al.,
1996), whereas, in the other, they are correlated with the forearc
basin deposits of the Great Valley Group (Hall, 1991; Barth and
Schneiderman, 1996; Saleeby, 1997). The third model involves
formation of the schists above a SW-dipping subduction zone
along which a continental sliver was sutured to North America
(Haxel and Dillon, 1978; Ehlig, 1981; Dillon et al., 1990).

One of the most critical places for understanding the tec-
tonic evolution of the Pelona–Orocopia–Rand Schists is the
Gavilan Hills area of southeasternmost California (Figs. 1–3)
(Haxel, 1977; Dillon et al., 1990; Simpson, 1990; Oyarzabal et
al., 1997). The Gavilan Hills are situated along a domal cul-
mination of the Chocolate Mountains anticlinorium within the
Picacho–Peter Kane Mountain area of Haxel (1977) and include
three crystalline lithotectonic packages (Figs. 1–3). Structurally
deepest is the Orocopia Schist, which underlies the Chocolate
Mountains fault. Above the schist is a thin slice of quartzofelds-
pathic to amphibolite gneiss derived from middle to deep levels
of the Mesozoic North American magmatic arc (Dillon, 1976;
Haxel, 1977; Dillon et al., 1990; Willis and Tosdal, 1992). The
Exhumation history of the Orocopia Schist and related rocks

Figure 1. A: Distribution of Pelona, Orocopia, and Rand Schists. These rocks sit structurally beneath Precambrian to Mesozoic igneous and metamorphic rocks of North American affinity and are exposed in windows through the shallowly dipping Vincent, Chocolate Mountains, Orocopia, and Rand faults. Abbreviations: AZ—Arizona, CA—California, CH—Chocolate Mountains, CTR—central Transverse Ranges, ETR—eastern Transverse Ranges, GH—Gavilan Hills, LA—Los Angeles, NV—Nevada, OR—Orocopia Mountains, RA—Rand Mountains, SG—San Gabriel Mountains, SP—Sierra Pelona, GF—Garlock fault, SAf—San Andreas fault. Modified from Haxel et al. (1985).

B: Distribution of Orocopia Schist, Winterhaven Formation, and metamorphosed sedimentary and volcanic rocks of Slumgullion in southeastern California and southwesternmost Arizona. Rocks of the upper plate of the Chocolate Mountains fault cannot be adequately portrayed at the scale of this map and are omitted. Modified from Haxel et al. (1985).

gneiss sits beneath the Gatuna fault, which has previously been considered to have steep dip, but which we argue is fundamentally a low-angle fault. Overlying the Gatuna fault are metasedimentary and metavolcanic rocks of the Jurassic (?) Winterhaven Formation, representing a shallow level of the Mesozoic arc (Haxel et al., 1985).

The Gavilan Hills are significant for two reasons. First, many segments of the Vincent–Chocolate Mountains fault in southeastern California, including the one in the Gavilan Hills, locally exhibit top-to-NE displacement, which is the principal observation used to support the model of SW-dipping subduction (Haxel and Dillon, 1978; Ehlig, 1981; Dillon et al., 1990). This interpretation is required, however, only if the northeast movement is related to underthrusting (Burchfiel and Davis, 1981; Crowell, 1981; Hamilton, 1987, 1988; Jacobson et al., 1996). In this regard, it is important to note that Simpson (1990) and Oyarzabal et al. (1997) concluded on the basis of microstructural studies that the Chocolate Mountains fault of the Gavilan Hills is actually a retrograde exhumation structure. Here, we present further structural, metamorphic, and thermochronologic data for the Orocopia Schist, gneiss, and Winterhaven Formation confirming that inference.

The Gavilan Hills are also important for constraining the exhumation history of the Pelona–Orocopia–Rand Schists. Potassium-argon and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of phengitic muscovite from across the Pelona–Orocopia–Rand Schist terrane indicate these rocks cooled to temperatures substantially below those of peak metamorphism by ca. 40–70 Ma (Ehlig, 1981; Jacobson, 1990). This has led some authors to invoke low-angle subduction associated with the Laramide orogeny as a principal factor driving tectonic denudation of the schist (Postlethwaite and Jacobson, 1987; Jacobson et al., 1988, 1996; Malin et al., 1995; Oyarzabal et al., 1997; Wood and Saleeby, 1997), analogous to models proposed for exhumation of the Franciscan Complex (Cloos, 1982; Platt, 1986; Jayko et al., 1987). On the other hand, with a few possible minor exceptions, schist detritus does not appear in the sedimentary record until Miocene time, at which point it becomes widespread (Ehlig et al., 1975; Dillon, 1976; Goodman and Malin, 1992). This observation suggests that middle Tertiary extension may have played an important role in bringing the schist to the surface (Frost et al., 1982, 1989; Hamilton, 1987, 1988). In the Gavilan Hills, both the Chocolate Mountains and Gatuna faults likely accommodated significant exhumation of the schist (Simpson, 1990; Oyarzabal et al., 1997). Rigorous determination of timing and relative apportionment of slip on these two structures, however, has previously been hampered by insufficient thermochronologic data. To help address this issue, we have undertaken detailed $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of hornblende, muscovite, biotite, and K-feldspar from both Orocopia Schist and gneiss.
Figure 2. Geology of the Picacho-Peter Kane Mountain area. Compiled from Haxel (1977), Crowe (1978), Haxel et al. (1985), Sherrod and Tosdal (1991), and unpublished work by D.R. Sherrod and R.M. Tosdal. See Figure 1 for location.
STRUCTURAL AND METAMORPHIC RELATIONSHIPS

Chocolate Mountains fault

The Chocolate Mountains fault is exposed along the north and east sides of the Gavilan Hills and beneath two small klippen of gneiss in the center of the range (Figs. 2–4). The fault locally dips up to 40°–50°, but map relationships (Fig. 2) indicate it is likely to be subhorizontal on a regional scale. Haxel (1977) and Dillon et al. (1990) considered that all exposures of the Chocolate Mountains fault in the Gavilan Hills were parts of a single, domed surface. In contrast, Oyarzabal et al. (1997) raised the possibility that the fault beneath the klippen is actually a slightly older and structurally deeper surface than the one along the margins of the dome. Oyarzabal et al.’s (1997)
suggestion was based on the distribution of minor folds. Specifically, folds with NNE–SSW trend are widely distributed in the schist, but rare in the gneiss, except within the klippen. This variation in degree of shared history between the schist and different parts of the gneiss can readily be explained if the gneiss consists of several slices juxtaposed with the schist at different times along an anastomosing series of faults. Nevertheless, all contacts between schist and gneiss exhibit retrograde metamorphism (to be described below), suggesting that even the fault beneath the klippen is related to exhumation, as opposed to being a remnant of the yet older burial thrust.

**Gatuna fault**

The Gatuna fault has generally been interpreted as an upper-crustal, high-angle normal fault of middle to late Tertiary age unrelated to the Chocolate Mountains fault (Haxel et al., 1986; Dillon et al., 1990; Simpson, 1990). However, very similar mylonitic textures present in gneiss adjacent to both the Chocolate Mountains and Gatuna faults led Oyarzabal et al. (1997) to speculate that the Gatuna fault had accommodated an earlier phase of ductile deformation. Oyarzabal et al. (1997), in fact, proposed that both faults were synchronously active and that subsequent cataclastic overprinting along the Gatuna fault resulted from more recent slip that produced the present juxtaposition of Winterhaven Formation against gneiss.

Irrespective of the number and age of movement events along the Gatuna fault, the continuous outcrop pattern of intraformational markers within the Winterhaven Formation around the north and east sides of the Gavilan Hills (Figs. 2–4) is difficult to explain unless the contact between gneiss and Winterhaven Formation is fundamentally low-angle and subparallel to the Chocolate Mountains fault. Although the surface traces of the Chocolate Mountains and Gatuna faults along the north side of the Gavilan Hills appear dissimilar (Figs. 3 and 4), this is largely an artifact of topography. The northern segment of the Chocolate Mountains fault separates Orocopia Schist and gneiss where they dip moderately northward. The schist and gneiss in this region define a prominent E–W-trending ridge cut by local deep canyons. In contrast, the Winterhaven Formation is easily eroded, with the consequence that the Gatuna fault traverses a region of subdued topography at the base of the north-facing ridge of gneiss and schist. Furthermore, the Gatuna fault is poorly exposed and its outcrop trace not well constrained. We examined the entire length of the Gatuna fault and locally performed hand-trenching to investigate dip. In those few areas where a determination could be made, dip appears approximately parallel to that of the nearby Chocolate Mountains fault (~40–50°), rather than ~80° as illustrated by Dillon et al. (1990) (their Figure 3).

Map relationships between the Winterhaven Formation and underlying gneiss and schist in the Gavilan Hills are similar to
those in the domal culmination between Little Picacho Wash and White Wash and along the west margin of the Ferguson Lake/Trigo Mountains schist area (Fig. 2). In the latter areas, Haxel et al. (1985, this volume) inferred that the Winterhaven Formation was underlain by a low-angle fault (Sortan fault; Fig. 2), which we interpret as a broad correlative of the Gatuna fault.

**Foliation and lineation**

The elongated dome in the Gavilan Hills is indicated, not just by outcrop pattern, but also by variations in the attitude of foliation in the schist, gneiss, and Winterhaven Formation (Fig. 3A). In addition to the first-order domal structure, the foliations crudely define several subsidiary antiforms and synforms trending approximately E–W in both the schist and Winterhaven Formation. Notably, the central klippen and eastern “flap” of gneiss represent a gentle synformal “keel” along the E–W mid-line of the dome.

Initial speculation that the Chocolate Mountains fault might not be the original thrust fault responsible for burial and metamorphism of the Orocompia Schist was based on regional considerations (Burchfiel and Davis, 1981; Crowell, 1981; Hamilton, 1987, 1988). The first direct evidence in the Gavilan Hills to support this contention was presented by Simpson (1990), who noted that early-formed features of ductile deformation are overprinted by later cataclastic ones. Subsequently, Oyarzabal et al. (1997) found that lineations in the Orocompia Schist adjacent to the Chocolate Mountains fault are parallel to lineations in the overlying gneiss, but discordant to ones in the schist away from the fault. They took this as evidence of two discrete deformations in the Orocompia Schist, one related to underthrusting, the other to exhumation. The lineation data reported by Oyarzabal et al. (1997) were obtained primarily from the western half of the Gavilan Hills and involved sampling of schist and gneiss, but not Winterhaven Formation. Here, we present their original measurements, along with new ones from all three units (Fig. 3B) (see also Stamp, 1997). Key observations include:

1. Lineation in the upper part of the Orocompia Schist clearly has a different orientation than that in the schist away from the Chocolate Mountains fault. The difference is least evident around the central klippen, but can be recognized along the length of the synformal trough to the east of the klippen. Along the north margin of the Gavilan Hills, the trend of lineation in the zone affected by the Chocolate Mountains fault ranges from ENE–WSW in the west to WNW–ESE in the east. This variation in trend of lineation along the length of the fault can be ascribed no more than partly to the doming event. This is evident from the eastern two-thirds of the fault segment within the area of Figure 3B. Here, the trend of lineation ranges from E–W to WNW–ESE without any significant change in attitude of foliation. Similarly, the difference in trend of lineation between the schist close to and far from the fault is much greater in the east (≈90°) than the west (≈30°).

2. Where measured, lineation in the gneiss is parallel to that in immediately adjacent schist. Unfortunately, no lineation data could be obtained from the thin, poorly exposed slivers of gneiss along the northeast side of the schist.

3. Lineation in the Winterhaven Formation is approximately parallel to that in the gneiss and uppermost schist, although this relationship is weakest along the westernmost parts of the Chocolate Mountains and Gatuna faults.

Overall, congruence of the lineation data from the three units is most easily explained by a degree of shared ductile deformation.

In the following sections, we describe the structure and metamorphism of the Orocompia Schist, gneiss, and Winterhaven Formation, individually. For the schist and gneiss, which have received considerable previous attention (Haxel, 1977; Haxel and Tosdal, 1986; Dillon et al., 1990; Simpson, 1990; Oyarzabal et al., 1997), we present only new observations or those critical to our main conclusions.

**Orocompia Schist**

Orocompia Schist of the Gavilan Hills is made up almost entirely of quartzofeldspathic schist. Scattered bodies of mafic schist, metachert, marble, and serpentinite comprise no more than one percent by volume and are not considered further. The exposed structural thickness of schist in the Gavilan Hills is only 300–400 m, although geophysical evidence suggests that Orocompia Schist in southeastern California likely extends to a depth of at least several kilometers (Morris, 1993).

**Structure**

Structurally deep schist (that more than ~100 m beneath the Chocolate Mountains fault) is characterized by a highly planar (flaggy) schistosity defined primarily by parallel alignment of phengitic muscovite and biotite and to a lesser degree by the arrangement of ovoid grains of quartz and feldspar. Schistosity is axial-planar to widespread, highly appressed isoclinal folds. A lineation in the structurally deep schist is defined by (1) elongated mineral grains, particularly of biotite, (2) color banding related to low-angle intersections of compositional layering and schistosity, and (3) a tendency to weather into elongated slabs. This is the lineation that defines the more northerly trends evident in Figure 3B.

Schist in the upper part of the section exhibits a wide range of textures. Part of it preserves the smooth, flaggy schistosity present away from the Chocolate Mountains fault, but much of it is overprinted by a younger fabric. Moderate overprinting is reflected by a “scaly” to “lumpy” fabric defined by highly sheared muscovite-rich domains preferentially exposed by weathering. The scaly fabric is highly characteristic of schist.
near the Chocolate Mountains fault. Haxel (1977) used the term “coarse schist” to describe the scaly texture and argued that it resulted from increased metamorphic grade near the Chocolate Mountains fault. However, the scaly schist typically exhibits protomylonitic to mylonitic fabric, as well as extensive replacement of biotite by chlorite and other mineralogic characteristics that lead us to infer a retrograde origin.

Relatively stronger overprinting of early, prograde schistosity is reflected by widespread development of prominent shear bands (cf. Simpson and Schmid, 1983; Lister and Snoke, 1984) with centimeter to decimeter spacing. The shear bands are oriented at low to moderate angles to preexisting schistosity, resulting in a tendency for the schist to weather into sigmoidal lenses. The shear bands have previously been studied in most detail along the western part of the Chocolate Mountains fault in the Gavilan Hills, where they exhibit overwhelmingly consistent top-to-NE sense of displacement (Dillon et al., 1990; Simpson, 1990; Oyarzabal et al., 1997). To the east, however, shear sense is oriented top-to-E to top-to-ESE, in sympathy with the spatial variation in trend of lineation (Fig. 3B). In all parts of the area, shear bands with antithetic sense of displacement are extremely rare (less than a few percent of the hundreds of total observations).

Lineation in the structurally high schist includes types similar to those described for the deeper schist (to be referred to as “early” lineations), but is also commonly defined by elongated smears of mica and fine ridges and grooves on schistosity surfaces (“late” lineations). Although most abundant within the structurally highest schist, late lineations are also present at deeper levels in mica-rich bulk compositions. Both early and late lineations in the upper part of the section trend clockwise relative to early lineations at deeper structural levels. Furthermore, where both types of lineation are present in the same outcrop, whether high or low in the section, late lineation is consistently oriented clockwise relative to early lineation.

As noted above, some of the most northerly trending lineations in structurally high schist occur adjacent to the central klippen of gneiss (Fig. 3B). This is probably due partly to particularly mica-poor composition of schist in this area. However, even mica-rich schist in the vicinity of the klippen does not show strong reorientation of the lineation.

Orocopia Schist within centimeters to several meters of the Chocolate Mountains fault typically exhibits several generations of mylonite to ultramylonite (Simpson, 1990; Oyarzabal et al., 1997). Early-formed mylonites tend to be coarser grained and show relatively high degrees of recovery and recrystallization. Later ones, besides being finer grained, exhibit stronger grain-shape asymmetries and occur in narrower zones. Lineation in mylonitic schist is commonly difficult to discern, but, where present, is parallel to the lineation in nearby nonmylonitic schist. Brittle shears at both the outcrop and thin-section scale locally overprint the mylonitic fabrics and are progressively more strongly developed along the eastern part of the Chocolate Mountains fault, particularly in the vicinity of the eastern flap of gneiss. In this area, orange-brown limonitic staining of the schist is common.

Metamorphism

The dominant prograde minerals in the quartzofeldspathic schist are quartz, albite to oligoclase, biotite, and phengitic muscovite (Table 1). Three subtypes of the quartzofeldspathic schist were distinguished based on relative proportions of biotite and muscovite, presence or absence of K-feldspar and hornblende, and various other mineralogic characteristics (Table 1). The ubiquitous presence of both albite and oligoclase clearly indicates metamorphism in the lowermost part (oligoclase zone) of the amphibolite facies (facies terminology of Graham and Powell, 1984). Application of the garnet-hornblende thermometer of Graham and Powell (1984) to Orocopia metabasites from the Gavilan Hills yielded an average temperature of 560 °C (Oyarzabal, 1996), similar to that determined by Graham and Powell (1984) for the oligoclase isograd in Pelona Schist from the Sierra Pelona area using the same thermometer.

The Pelona–Orocopia–Rand Schists typically exhibit inverted metamorphic zonation; i.e., peak temperature of metamorphism tends to increase structurally upward (Ehlig, 1958; Graham and England, 1976; Jacobson, 1983a, 1995; Graham and Powell, 1984). The maximum range of metamorphic facies occurs in those schist bodies for which exposed structural thickness is on the order of several kilometers. In such areas, metamorphism typically ranges from epidote-blueschist or green-schist facies at the base of the exposed structural section to albite-epidote-amphibolite or oligoclase-amphibolite facies at the top. The lower-amphibolite-facies metamorphism observed for the relatively small thickness of schist exposed in the Gavilan Hills is thus consistent with that seen at the top of the structural section in other bodies of Pelona–Orocopia–Rand Schist.

Overprinting of prograde mineral assemblages in the Orocopia Schist is found throughout the area, but is strongest in structurally high levels adjacent to the Chocolate Mountains fault. Here, chlorite commonly replaces both garnet and biotite, particularly in association with development of the late lineation. Some degree of chlorite replacement of garnet is observed throughout the schist, even where there is little additional mineralogic or textural evidence of retrogression. In samples from the lower part of the section, the chlorite forms pseudomorphs after euhedral to subhedral garnet. With approach to the Chocolate Mountains fault however, the extent of garnet replacement increases, and aggregates of chlorite and relict garnet define elliptical shapes indicating that retrogression occurred during or prior to deformation associated with the Chocolate Mountains fault. Chlorite is particularly abundant in samples from discrete shear zones, those showing strong development of the scaly schistosity, and hinges of open-to-tight folds. In detail,
the retrograde reaction is likely muscovite + biotite + quartz + H₂O ⇌ phengite + chloride (Ernst, 1963; Velde, 1965; Powell and Evans, 1983).

It is important to note that, whereas chloride abundance is broadly correlated with proximity to the Chocolate Mountains fault, there are many structurally high samples in which biotite shows relatively little replacement by chloride. This observation can be understood in terms of the following relationships. First, not all bulk compositions are suitable for development of chloride. In the many samples with K-feldspar, decreasing temperature should lead to breakdown of biotite by the reaction muscovite + biotite + K-feldspar + quartz + H₂O ⇌ phengite (Ernst, 1963), which produces no obviously retrograde mineral (i.e., chloride). In addition, at least the initial stages of retrogression associated with slip along the Chocolate Mountains fault appear to have occurred while the schists were still relatively hot (Oyarzabal et al., 1997). Assuming that retrogression was promoted by deformation, then samples from shear zones or fold hinges with no or only small amounts of chloride might have been deformed early on, and at high enough temperature, that biotite was still stable. Finally, the far greater abundance of secondary calcite (up to several tens of percent) within schist adjacent to the Chocolate Mountains fault, particularly in strongly mylonitic samples, suggests that CO₂-rich fluids along the fault zone may have limited chloride-forming hydration reactions.

Most biotite in quartzofeldspathic schist from the Gavilan Hills exhibits the reddish-brown to brown maximum absorption colors typical of this mineral at medium grades of metamorphism (Guidotti, 1984). However, retrograde light- to medium-green biotite is also present. Green biotite is most abundant in strongly mylonitic schist and in quartzofeldspathic schist cut by late-stage veins (below). Samples with abundant green biotite tend to be chlorite-free and have relatively little muscovite, despite the fact that the mylonites and veins represent a very late stage in the deformation of the schist. The TiO₂ contents of the green biotites (0.2–0.3 wt%) are an order of magnitude lower than those yielded by the prograde biotite and indicate formation at greenschist facies conditions (Guidotti, 1984).

Further constraints on retrograde history are indicated by textural relations between titanite and rutile. Both phases occur in prograde assemblages, titanite being the dominant of the two (Table 1). Prograde rutile is typically rimmed by titanite, a common retrograde texture in Pelona–Orocopia–Rand Schist (Jacobson, 1980; Jacobson and Dawson, 1995). However, in the immediate vicinity of the Chocolate Mountains fault, secondary rutile occurs in association with calcite as a fine granular replacement of titanite. This type of rutile is most prevalent in mylonitic rocks. We consider it to reflect the reaction titanite + CO₂ ⇌ quartz + rutile + calcite, and to confirm that fluids near the fault were enriched in CO₂ Elevated CO₂ in fluids near

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<th>Percent</th>
<th>Rock type</th>
<th>Description</th>
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<tr>
<td>70</td>
<td>Qtz-Plg-Bio-Mus schist</td>
<td>Subequal Bio and Mus impart salt and pepper aspect. Mus in lenses, layers, and</td>
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<tr>
<td>70</td>
<td>Hbd-Plg-Ep-Bio Gneiss</td>
<td>Subequal Plg, Qtz, Bio, and Ep. Secondary Mus and Chl. Accessories include</td>
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<tr>
<td>30</td>
<td>Hbd-Plg-Ep-Qtz Gneiss</td>
<td>Subequal blue-green Hbd and Plg with subordinate Ep, Bio, and minor Qtz.</td>
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<tr>
<td></td>
<td></td>
<td>Accessory Chl is common. Equivalent to &quot;mafic gray schist&quot; of Haxel (1977).</td>
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**Table 1. Metamorphic Rocks of the Gavilan Hills**

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<tbody>
<tr>
<td>70</td>
<td>Qtz-Plg-Bio-Mus schist</td>
<td>Subequal Bio and Mus impart salt and pepper aspect. Mus in lenses, layers, and</td>
</tr>
<tr>
<td>70</td>
<td>Hbd-Plg-Ep-Bio Gneiss</td>
<td>Subequal Plg, Qtz, Bio, and Ep. Secondary Mus and Chl. Accessories include</td>
</tr>
<tr>
<td>30</td>
<td>Hbd-Plg-Ep-Qtz Gneiss</td>
<td>Subequal blue-green Hbd and Plg with subordinate Ep, Bio, and minor Qtz.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accessory Chl is common. Equivalent to &quot;mafic gray schist&quot; of Haxel (1977).</td>
</tr>
</tbody>
</table>

Most biotite in quartzofeldspathic schist from the Gavilan Hills exhibits the reddish-brown to brown maximum absorption colors typical of this mineral at medium grades of metamorphism (Guidotti, 1984). However, retrograde light- to medium-green biotite is also present. Green biotite is most abundant in strongly mylonitic schist and in quartzofeldspathic schist cut by late-stage veins (below). Samples with abundant green biotite tend to be chlorite-free and have relatively little muscovite, despite the fact that the mylonites and veins represent a very late stage in the deformation of the schist. The TiO₂ contents of the green biotites (0.2–0.3 wt%) are an order of magnitude lower than those yielded by the prograde biotite and indicate formation at greenschist facies conditions (Guidotti, 1984).

Further constraints on retrograde history are indicated by textural relations between titanite and rutile. Both phases occur in prograde assemblages, titanite being the dominant of the two (Table 1). Prograde rutile is typically rimmed by titanite, a common retrograde texture in Pelona–Orocopia–Rand Schist (Jacobson, 1980; Jacobson and Dawson, 1995). However, in the immediate vicinity of the Chocolate Mountains fault, secondary rutile occurs in association with calcite as a fine granular replacement of titanite. This type of rutile is most prevalent in mylonitic rocks. We consider it to reflect the reaction titanite + CO₂ ⇌ quartz + rutile + calcite, and to confirm that fluids near the fault were enriched in CO₂ Elevated CO₂ in fluids near
the fault is also indicated by breakdown of clinozoisite to calcite, chlorite, and sericite.

Carbonate and/or quartz veins occur throughout the schist but are most abundant near the Chocolate Mountains fault. Although they exhibit a wide range of orientations relative to foliation in the schist, many are at a high angle to layering. Some include up to a few percent pyrite, which imparts a distinctive yellow to brown color where weathered. In some veins, calcite and quartz are euhedral, suggesting infilling of open fractures. A less common variety of vein is composed of quartz and plagioclase or plagioclase alone. Plagioclase in these veins occurs as polygonal, inclusion-free grains that are spatially associated with green biotite and are texturally distinct from the poikiloblasts typical of unaltered schist. In addition to veins, the schist also contains planar “bleached” zones adjacent to fractures and minor faults. The bleached zones consist of schist from which biotite and muscovite have been dissolved, leaving behind a rock rich in quartz and plagioclase. There is a complete gradation between normal and bleached schist. Plagioclase in the bleached zones occurs as poikiloblasts identical in form to those in the adjacent schist, clearly indicating the parentage of this rock. Biotite in schist adjacent to the bleached zones is generally the green variety.

A final distinctive vein type present primarily in uppermost schist in the central to eastern parts of the Gavilan Hills contains fibrous, grayish-blue sodic amphibole. The veins are clearly retrograde in that they crosscut the foliation at a high angle. The amphibole is intermediate in composition between riebeckite and magnesioriebeckite, contains little Al, and, thus, has no implications for pressure of formation (Ernst, 1968). It is typically accompanied by quartz and/or plagioclase, with sodic pyroxene (aegerine) occurring as an additional constituent in some cases. The sodic amphibole commonly permeates the schist adjacent to the veins, where it replaces biotite, mimetically preserving foliation. Biotite within millimeters of sodic amphibole tends to be the green variety.

Gneiss

The gneiss comprises a heterogeneous mix of centimeter- to decimeter-scale interlayers of felsic (quartzofeldspathic), intermediate, and mafic composition (Table 1). Mafic and intermediate lithologies are considerably more abundant than in the schist, whereas metachert and serpentine are absent. Furthermore, the gneiss is generally less micaceous than the schist and has a much higher ratio of biotite to muscovite. Except where overprinted by deformation related to the Chocolate Mountains and Gatuna faults, the gneiss is also higher in metamorphic grade and coarser grained than the schist. Maximum structural thickness of gneiss within the Gavilan Hills is ~120 m.

Structure

Away from the Chocolate Mountains and Gatuna faults, foliation in the gneiss is defined principally by compositional layering. Some of the gneiss has a mylonitic aspect defined by centimeter or larger ovoid plagioclase porphyroclasts. In thin section, these rocks contain coarse, polygonal quartz and show no evidence of retrograde metamorphism. This coarse fabric is thought to be older than and distinct from a finer-grained protomylonitic to ultramylonitic fabric that is pervasive adjacent to both the Chocolate Mountains and Gatuna faults and more weakly developed through the gneiss as a whole. The finer-grained fabric is associated with retrograde metamorphism.

No lineation was found in association with the early, prograde fabrics. Retrograde lineation is defined by streaks of mica and chlorite on phyllosilicate-rich seams in quartzofeldspathic rocks and parallel alignment of relic hornblende grains in intermediate to mafic lithologies (Oyarzabal et al., 1997).

The gneiss contains small amounts of a relatively muscovite-rich rock type that, where sheared, appears virtually identical to the scaly Orocopia Schist. This variety of gneiss locally occurs immediately adjacent to Orocopia Schist, making the contact between schist and gneiss difficult to pinpoint.

Brittle shear zones are common in the gneiss along the Chocolate Mountains fault, and, as in the schist, increase in abundance toward the east. Brittle deformation is even more strongly developed adjacent to the Gatuna fault, where the gneiss is typically converted to foliated cataclasite as much as 5–10 m thick (Simpson, 1990; Oyarzabal et al., 1997).

METAMORPHISM

Prograde assemblages for various lithologies of gneiss are indicated in Table 1. The assemblage Al-rich hornblende + plagioclase indicates metamorphism in the middle to upper amphibolite facies (Oyarzabal, 1996). Overprinting of prograde assemblages is widespread in all compositions of the gneiss and is locally quite intense, particularly in the immediate vicinity of both the Chocolate Mountains and Gatuna faults. As in the Orocopia Schist, one of the most obvious effects of retrograde metamorphism is the partial to complete replacement of biotite by chlorite. Also prominent is the partial replacement of plagioclase by muscovite ± fine-grained clinozoisite (“saussurite”) ± calcite. Grain size of the muscovite ranges from fine (sericitic) to nearly as large as that of the host plagioclase grains. The muscovite flakes are oriented either randomly, in radiating clusters, or parallel to two or more sets of crystallographic planes within individual crystals of plagioclase. Unaltered plagioclase has composition in the range An20-An40, whereas altered plagioclase has anorthite content of <10 mole percent. In general, the breakdown of biotite and plagioclase are strongly correlated within individual samples.

Because most samples of gneiss do not contain primary muscovite, the breakdown of biotite and growth of white mica and chlorite must have involved reactions different from those inferred for the Orocopia Schist (above). Considering the strong correlation between breakdown of biotite and plagioclase, we propose the two reactions:
Mineral compositions are simplified (e.g., Fe\(^{2+}\) and Fe\(^{3+}\) for Mg and Fe\(^{3+}\) for Al), but similar to those actually measured. Reactions (1) and (2) are based on assumption of a closed system at the thin-section scale, other than for fluid. Local mobility of potassium in those fluids seems required by the relatively few samples for which replacement of plagioclase by muscovite and biotite by chlorite are not coupled.

An additional sign of retrograde metamorphism in the mafic to intermediate gneisses is the local replacement of hornblende by actinolite. However, typically no more than a few percent of hornblende is altered in this fashion, even in rocks where biotite and plagioclase are extensively to completely altered. Hornblende in the gneiss is paragastic (Oyarzabal, 1996), indicative of moderately high-grade metamorphism (Leake, 1965; Ernst and Liu, 1998). It seems inconceivable that paragastic hornblende could have been stable at the relatively low-grade, greenschist-facies conditions implied by the other retrograde reactions. Instead, we conclude that the widespread preservation of hornblende is evidence for incomplete chemical reequilibration, even in rocks strongly deformed during movement of the Chocolate Mountains fault. Extensive metastable persistence of hornblende has also been observed in mylonitic gneiss above the Vincent thrust in the San Gabriel Mountains (Jacobson, 1997).

Green biotite identical in appearance to that in the Orocopia Schist is also present in the gneiss. It is particularly abundant in strongly mylonitic samples adjacent to both the Chocolate Mountains and Gatuna faults. Another similarity with the schist is the local occurrence of sodic amphibole-bearing veins oriented at a high angle to foliation. Such veins are common within the two klippen in the center of the area and in the flap of gneiss at the east end of the Gavilan Hills, but rare in the northern strip of gneiss. As in the schist, sodic amphibole permeates country rock adjacent to veins, where it mimetically replaces mafic minerals aligned in the foliation. Alkali metasomatism is exceptionally well developed in ultramylonite at the top of the gneiss within the southeasternmost corner of Figure 3.

**Winterhaven Formation**

The Winterhaven Formation is most probably Middle and/or Late Jurassic in age and likely correlates with the basal part of the McCoy Mountains Formation to the north and with the little-known metasedimentary and metavolcanic rocks of Slumgullion in southwesternmost Arizona (Fig. 1) (Harding and Conney, 1985; Haxel et al., 1985; Tosdal et al., 1989; Grubensky et al., 1993; Tosdal and Stone, 1994). In the type locality between White Wash and Little Picacho Wash (Fig. 2), the formation consists of a basal trachydacite member, a medial quartz arenite member, and an upper argillitic siltstone member (only the volcanic member is discriminated in Figures 2–4) (Haxel, 1977; Haxel et al., 1985). In the Gavilan Hills, the volcanic and quartz arenite members are locally excised by faults. In addition to the rock types indicated by the member names, the Winterhaven Formation also includes sandy limestone, graywacke, argillitic siltstone, silty argillite, conglomeratic sandstone, and conglomerate (Haxel et al., 1985).

**Structure**

Haxel et al. (1985) described two regions within the Picacho–Peter Kane Mountain area where deformation of the Winterhaven Formation is relatively intense. One is along the northern branch of the Chocolate Mountains anticlinorium, where the unit is folded into a macroscopic, E–W trending, south-facing, overturned syncline (Fig. 2) with axial-planar cleavage. The other is in the vicinity of Julian Wash and lower Marcus Wash, adjacent to a unit that Haxel et al. (1985) named the "granite of Marcus Wash" (Fig. 2). The “granite of Marcus Wash” was initially interpreted to have intruded the Winterhaven Formation, but is now known to be composed of metamorphosed quartz porphyritic volcanic rocks and shallow plutons of Jurassic age that form the depositional base of the Winterhaven Formation (R.M. Tosdal, 1997, written commun.).

Outside the above two regions, Haxel et al. (1985) concluded that most of the Winterhaven Formation, including that in the area of the Gavilan Hills, was not penetratively deformed. However, our observations of the Winterhaven Formation in the Gavilan Hills area indicate that it does contain a pervasive tectonite fabric, albeit one that is markedly less intense than that in the Orocopia Schist and banded gneiss. This disagreement relates to opposing interpretations of planar “fissility” in the argillitic siltstone and silty argillite. Previously considered
to be bedding, we interpret the fissility as cleavage on the basis of the following observations:

1. Subtle color banding that appears to us to represent primary bedding occurs at low to high angles to the fissility.

2. The argillitic siltstone and silty argillite locally contain layers of quartz arenite a few decimeters to approximately a meter in thickness, which we also interpret as sedimentary beds. The quartz arenite layers are commonly highly oblique to fissility in the siltstone and argillite.

3. The fissility of the argillitic siltstone and silty argillite is axial planar to scarce fold hinges.

4. Rare layers of pelite exhibit an unambiguous metamorphic fabric. The pelite must have acted to concentrate deformation, with the fine-grained clays of the original sediment recrystallizing more readily than the detrital sand grains abundant in much of the rest of the formation. The pelite contains a well-developed phyllitic schistosity and strong lineation. The schistosity is parallel to the less regular fissility in the coarser rock units.

5. The argillitic siltstone and silty argillite locally contain en echelon arrays of decimeter carbonate lenses, with individual lenses oriented parallel to local fissility. The arrays appear to represent dismembered and transposed carbonate layers, which may have been either primary sedimentary beds or diagenetic features.

Lineation is not prominent in most of the Winterhaven Formation surrounding the Gavilan Hills, owing to the generally mild deformation, the silt- and sand-rich bulk compositions, and later brittle overprinting. The strongest lineation is found in the pelite, and is defined by alignment of sericite and elongated sedimentary intraclasts. Pelite is most abundant near the base of the Winterhaven Formation in the Gavilan Hills (i.e., close to the Gatuna fault), which allows comparison with lineation in the Oroopia Schist and gneiss. Lineation is also defined by elongated chloritic clots on cleavage surfaces of argillitic siltstone and silty argillite and by the elongated carbonate lenses described above. Both the chloritic and carbonate lenses locally contain mineral streaks aligned parallel to the long dimension of the lenses.

The Winterhaven Formation in the Gavilan Hills exhibits a strong brittle overprint. This is partly manifested by abundant joints spaced at the centimeter to decimeter scale. Even more distinctive, however, is that many outcrops display a highly sheared character related to an abundance of steeply to shallowly dipping, planar to anastomosing faults with decimeter-to-meter-scale spacing. The faults are associated with breccia and/or gouge and show no evidence of ductile deformation. Offsets are generally difficult to determine, but range from less than a meter to greater than the extent of typical outcrops (meters to a few tens of meters). Although not present at all outcrops, the brittle overprint shows no systematic spatial distribution. Additional brittle deformation within the Winterhaven Formation occurs within meters of the Gatuna fault, where rocks are typically converted entirely to breccia or gouge.

**Metamorphism**

Clastic rocks (silty argillites, argillitic siltstones, siltstones, and sandstones) in the Winterhaven Formation are characterized by silt- to sand-sized detrital grains surrounded by fine, recrystallized matrix. The most abundant detrital mineral is quartz, which occurs as single crystals, as polycrystalline aggregates with or without feldspar, and in chert fragments. Plagioclase, much of it altered to sericite, is also common. Clastic grains of potassium feldspar are widespread, but less abundant than plagioclase. Detrital muscovite is present in some samples, but biotite is noticeably absent, as are other mafic minerals. A moderate number of samples include felsic volcanic fragments. Interpretation of the above grain types as detrital is based partly on the extreme range of grain size between samples, which is readily explained by sedimentary sorting. The chert and volcanic fragments, as well as quartz grains showing epitaxial overgrowths on rounded, iron-stained cores, provide further evidence that detrital material is widely preserved.

Recrystallized matrix consists of quartz, feldspar (albite?), calcite, muscovite/sericite, and chlorine. The quartz, feldspar, and calcite range from polygonal to elongate parallel to cleavage (aspect ratios up to ~2:1). The sericite commonly occurs as rounded blebs that are probably pseudomorphs after plagioclase. Chlorite is present in most samples, although easily overlooked because of its pale color and fine grain size. Many samples contain a percent or so of clear, subhedral epidote of probable metamorphic origin.

Despite the uncertainties associated with interpreting incompletely recrystallized rocks, the common presence of metamorphic chlorite, muscovite, and quartz, but absence of biotite, seems indicative of conditions in the lower greenschist facies (Spear, 1993). This is a lower grade than observed elsewhere in the Picacho–Peter Kane Mountain area, where much of the Winterhaven Formation contains metamorphic biotite (Haxel et al., 1985).

The Winterhaven Formation of the Gavilan Hills area includes widely scattered metamorphosed mafic dikes or sills. These are thoroughly recrystallized and characterized by the assemblage quartz, plagioclase (albite?), chlorine, epidote, and calcite. As with the clastic rocks, this assemblage is consistent with metamorphism in the lower greenschist facies (Harte and Graham, 1975).

**THERMAL HISTORY OF THE GAVILAN HILLS**

Structural and petrologic data presented above confirm previous inferences (Simpson, 1990; Jacobson et al., 1996; Oyarzabal et al., 1997) that the Chocolate Mountains fault in the Gavilan Hills postdates the prograde metamorphism of Oroopia Schist. Less certain, however, is the age of slip along the fault, which has been considered to be either Late Cretaceous-early Tertiary (Jacobson et al., 1996; Oyarzabal et al., 1997) or middle Tertiary (Frost et al., 1982, 1989; Hamilton, 1987,
1GSA Data Repository item 2002122, Analytical methods, sample list, and 40Ar/39Ar furnace step-heating results, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado, 80301, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

Exhumation history of the Orocopia Schist and related rocks

Interpretation of thermal history based upon argon isotopic data from K-bearing minerals depends significantly upon our knowledge of the Ar diffusion properties of these materials both in nature and during laboratory step-heating. Potassium feldspar is a favorable material for detailed thermal history analysis between ~350 and 150 °C because it characteristically remains stable during vacuum heating until melting at temperatures above ~1100 °C and generally exhibits the high degree of correlation of age and laboratory diffusion properties that is expected to occur when laboratory-determined Ar diffusion properties adequately represent Ar retention properties in nature (Lovera et al., 1993, 1997, 2001). For K-feldspars that exhibit the expected diffusion behavior, the multidiffusion domain (MDD) model can be reliably applied to recover thermal histories (see Lovera et al., 1997, 2001).

Detailed interpretation of step-heating results from hornblende, muscovite, and biotite is problematic because Ar release during in vacuo heating is known to occur as the hydrous phases decompose (McDougall and Harrison, 1999). Physical changes such as basal delamination that attend dehydroxylation (Vedder and Wilkens, 1969) will tend to homogenize naturally imposed age gradients. Hornblende and biotite are most severely affected by this process (Gaber et al., 1988; Lee et al., 1991). Muscovite tends to fare better due to the existence of a metastable dioctahedral dehydroxylate phase (Udagawa, 1974) with similar physical and chemical properties to muscovite (Keppler, 1990), minimizing, but not totally precluding, the structural modifications experienced during dehydroxylation.

A consequence of the instability of amphibole and mica during in vacuo heating is that “plateaus” in the age spectra of these phases possess no clear significance because they are an expected result of structural failure during dehydroxylation. Similarly, isochron data from slowly cooled metamorphic phases can not be simply interpreted due to the likelihood that apparently homogeneous radiogenic 40Ar concentrations are an experimental artifact. For this reason, the timing of bulk closure for retention of radiogenic 40Ar (40Ar*) retention is best approximated by total gas ages provided that age spectra reveal no evidence for contamination by excess 40Ar* (40ArE) and that recrystallization at or below conditions for 40Ar closure is not indicated from textural observations. The conditions of bulk Ar closure in micas must be inferred from extrapolation of high-temperature laboratory experiments and field studies and consequently are known only approximately. We assume monotonic cooling and use representative bulk closure temperatures of 525 ± 50 °C, 400 ± 50 °C, and 350 ± 50 °C for hornblende, muscovite, and biotite, respectively (see McDougall and Harrison, 1999). We recognize that compositional (e.g., Grove and Harrison, 1996) and other effects could alter these estimates of bulk closure and hence regard them only as provisional estimates. We believe that the assumption of monotonic cooling is well justified. Despite the widespread distribution of middle Tertiary volcanic rocks in the Picacho-Peter Kane Mountain area as a whole (Fig. 2), we have observed no middle Tertiary igneous rocks cutting the Orocopia Schist, gneiss, or Winterhaven Formation within the Gavilan Hills area. We thus find no compelling reason to suspect that the 40Ar/39Ar ages were reset by magmatism.

Hornblende

Hand-selected aggregates of hornblende were analyzed from five mafic schists from the Orocopia Schist and three amphibolites from the gneiss (Fig. 4B; also shown is the one hornblende age determined by Jacobson, 1990). As indicated in Figure 5, all samples tend to exhibit young ages during the initial low-temperature stages of 39Ar release that are associated with low Ca/K values (<10). This is a commonly observed phenomenon in metamorphic hornblendes from high P/T settings (e.g., Ross and Sharp, 1988; Baldwin and Harrison, 1992; Grove and Bebout, 1995) and has been interpreted by most authors as reflecting the existence of finely intergrown, K-rich phases. Although we did attempt to screen problematic samples prior to 40Ar/39Ar analysis by performing x-ray diffraction measurements to examine our hornblendes for evidence of
intergrown mica, none was detected. The observed degradation could be produced by only ~1% contamination, however, and this level of abundance is below the limit of detection of x-ray diffraction.

The bulk of argon release from our hornblende samples occurred at relatively high temperature (beginning at about the 990 °C step) and is characterized by uniformly high Ca/K values characteristic of hornblende (> ~10). Because in vacuo Ar release from hornblende is expected to have these characteristics (see Lee et al., 1991), we neglected the low-temperature step-heating results and focused our interpretation upon gas released beginning with the 990 °C step. Integrated ages were calculated by weighting the ages of individual high-temperature steps by the associated quantity of 39Ar release. Uncertainties were calculated in an equivalent manner. We processed the hornblende data in this way because we wished to ensure that the calculated ages and uncertainties would be compatible with those determined for the other phases. The high-temperature portions of hornblende age spectra obtained from the gneiss are relatively flat (Fig. 5) and yield integrated ages between 59 and 64 Ma (Fig. 4B, Table 2). In contrast, amphiboles from the Orocopia Schist display moderate age gradients and yield younger overall integrated ages (53–59 Ma).

**Muscovite**

Separates of phengitic muscovite were analyzed from 11 samples of Orocopia Schist and five of gneiss (Figs. 4C and 6; Table 2). Roughly half the samples exhibit relatively pristine prograde metamorphic fabrics. The remainder show moderate to strong retrogression and shearing related to the Chocolate Mountains fault. Total gas ages are similar for the gneiss and
schist, ranging from 44 to 50 Ma. Argon release spectra for virtually all samples exhibit a steep age gradient over the initial 20% of gas release starting at ca. 30 Ma (Fig. 6). There is a distinct tendency for samples from the eastern part of the area to exhibit more pronounced age gradients and lower overall total gas ages relative to those along the northern contact. Although none of the measured age spectra exhibit characteristics associated with excess argon (e.g., U-shaped spectra), we cannot absolutely conclude that the results are unaffected by \(^{40}\)Ar\(_{\text{E}}\) contamination.

Given the high temperatures indicated by the hornblende results to have existed prior to Ar closure in muscovite, we consider that the primary role of recrystallization has been to reduce the effective diffusive length scale for Ar transport (e.g., Goodwin and Renne, 1991). We believe that this effect explains the younger (44 Ma) age obtained from a highly sheared sample proximal to the Chocolate Mountains fault (sample 1090; Fig. 4; Table 2). In fact, the inferred cooling (>150 °C) from peak-grade metamorphism likely occurred over a narrow interval given the similarity of the temperatures of hornblende Ar closure and lowermost (oligoclase zone) amphibolite facies metamorphism indicated for the schist. The rapid cooling that occurred immediately prior to Ar closure in muscovite allows us to rule out age mixing effects of prograde and retrograde micas as described by Wijbrans and McDougall (1986), as these require protracted cooling at significantly lower temperatures.
Biotite

Separates of biotite were analyzed from nine samples of schist and six of gneiss (Figs. 4D and 6; Table 2). Seven of the samples display relatively undisturbed prograde metamorphic fabrics, five exhibit a moderate degree of shearing and retrogression related to the Chocolate Mountains fault, one is a strongly mylonitic gneiss along the Gatuna fault, and two are from schist adjacent to late veins. Biotite in the strongly mylonitic gneiss is optically intermediate between the red-brown and green varieties. That in the two vein samples is the green type. One of these samples (25B) includes sodic amphibole.

Biotite release spectra are similar in form to those from muscovite, but younger in age (Fig. 6). Excluding the one mylonite, total gas ages of biotites from the gneiss are relatively uniform, ranging from 40 to 45 Ma (Fig. 4D; Table 2). In contrast, biotite ages from the schist range from 31 to 42 Ma. They are oldest in the northwest and young systematically to the south and east. As a consequence, biotite ages from the schist and gneiss are essentially concordant along the segments of the Chocolate Mountains fault in the northwestern and central parts of the area, but strongly discordant in the east (Fig. 4D). The strong contrast in bulk age in the east indicates differential motion between the schist and gneiss subsequent to cooling below ~350, consistent with the more highly overprinted nature of the Chocolate Mountains fault in this area (above).

To a first order, we interpret the spatial variation of biotite ages as a consequence of exposure of progressively deeper structural levels of the schist both to the south and to the east. Provided that slow cooling occurred within the closure interval for Ar retention in biotite, small differences in structural level could easily explain the large spread in age (see Quidelleur et al., 1997). There are, however, exceptions to the simple trends described above that could be explained by recrystallization.
effects. For example, the biotite sampled from the mylonite at the top of the gneiss (sample 1243) is anomalously young compared to nearby samples of both schist and gneiss. Whereas we attribute the young age of this sample to reduced diffusion dimension due to shearing (e.g., Goodwin and Renne, 1991), we recognize that recrystallization may have been important, as the reduced K$_2$O content of this sample is consistent with significant alteration to chlorite. Similarly, green biotites may have formed at temperatures within the closure interval for Ar retention. Total gas ages for the green biotites analyzed from samples 25B and 1243, collected adjacent to late veins, are among the youngest obtained for biotite (31 and 34 Ma). Although recrystallization rather than slow cooling might be considered to have controlled the $^{40}$Ar/$^{39}$Ar ages obtained for these samples, we point out that red-brown, prograde biotites from this area (samples 1021 and 1026) also gave similarly young ages (32 and 33 Ma, respectively; Table 2). Biotite in the latter two samples is in textural equilibrium with muscovite having $^{40}$Ar/$^{39}$Ar ages of 48–49 Ma. Hence, while we provisionally interpret the ages from all the biotite samples as reflecting slow cooling, we recommend that a certain degree of caution be employed in interpreting all the results solely in terms of volume diffusion.

**K-Feldspar**

Two samples of K-feldspar were analyzed (samples 82 and 230). Sample 82 produced a release spectrum with an intermediate age maximum (Fig. 6). Such a feature is inconsistent with volume diffusion and indicates that the sample should not be quantitatively interpreted using the MDD approach (Lovera et al., 2001). We note, however, that the total gas age yielded by this sample (32 Ma; Table 2) is similar to that obtained from sample 230 (29 Ma). The latter sample is well behaved (Fig. 7A, B) and, hence, amenable to MDD analysis. After correction for initial low-temperature Cl-correlated excess $^{40}$Ar (Fig. 7A, C) following the approach of Harrison et al. (1994), we modeled the Ar diffusion properties of this sample, propagating uncertainties in the domain distribution parameters (Fig. 7B) as outlined in Lovera et al. (1997). Applying the restriction of monotonic cooling, we then calculated 50 best-fit thermal histories by least-squares fitting of the corrected age spectrum using 10 equivalent sets of MDD parameters (Fig. 7D) (see Lovera et al., 1997). Shown in Figure 7D are the 90% confidence intervals for the median and overall distribution of calculated thermal histories. As previously discussed, the assumption of

![Figure 7. Multidiffusion domain (MDD) model results for K-feldspar from Sample 230. See Lovera et al. (1997) for procedures employed to extract thermal history information from this sample under the assumption of monotonic cooling. A: Measured age spectrum and corresponding MDD model fits. Note that we have corrected the initial segment of the age spectrum for Cl-correlated excess $^{40}$Ar ($^{40}$ArE; see Harrison et al., 1994). B: Measured Arrhenius parameters and MDD model fits. Data used to estimate diffusion parameters are indicated. Short vertical ticks in the open circles represent ± 1σ uncertainties in the measured values. C: Correlated relationship between $^{40}$ArE and Cl/K used to correct age spectrum. D: Monotonic cooling histories corresponding to best-fit MDD age spectra shown in A above.](image-url)
monotonic cooling appears to us to be highly reasonable for the Gavilan Hills.

**Integrated thermal history results**

Our interpretation of the thermal history of the Gavilan Hills is presented in Figure 8. Here we have combined the temperature-time path inferred from K-feldspar (Fig. 7D) with bulk estimates from hornblende, muscovite, biotite, and apatite (fission track) from this and previous studies (Jacobson, 1990; Oyarzabal et al., 1997). Additional constraints such as the peak temperature of metamorphism indicated for the schist (~560 °C; Oyarzabal et al., 1997), and the depositional age of the protolith (<72 Ma; Grove et al., 2000) have influenced us in estimating the form of the prograde history. We caution the reader that differences related to structural position are masked because we have integrated results from the entire area. Despite this, it should be immediately evident that metamorphic rocks of the Gavilan Hills experienced a two-phase exhumation history indicated by rapid cooling from <60 Ma to 44 Ma and from 28 to 24 Ma.

As noted above, hornblendes from the gneiss yield older total gas ages and flatter release spectra than those from the Orocopia Schist. These differences suggest that the schist experienced protracted residence within the closure interval for Ar retention (525 ± 50 °C; McDougall and Harrison, 1999), whereas the gneiss cooled somewhat earlier and more rapidly through this interval. This requires that juxtaposition of the schist and gneiss occurred at temperatures below hornblende closure (i.e., under retrograde conditions) and places an upper constraint on the time at which the two units were brought together (Fig. 8). Although the detailed nature of the contrasting high-temperature thermal histories experienced by the schist and gneiss is not well constrained by our ⁴⁰Ar/³⁹Ar results, the probable form of the thermal histories can be reasonably inferred from numerical simulations of underthrusting and accretion (e.g., see Figure 8 in Harrison et al., 1998). In contrast to the situation for hornblende, muscovite ages from the schist and gneiss exhibit a strong degree of overlap (Figs. 4C and 6; Table 2). We take this as evidence that the schist and gneiss were in their present relative positions by the time of bulk closure of argon diffusion in muscovite at 48 ± 2 Ma. Based upon the structural and metamorphic context of our sampling, we conclude that it is likely that a substantial part of the early Tertiary phase of rapid cooling of the Orocopia Schist, which involved a drop in temperature of ~200 °C between 60 and 44 Ma (Fig. 8), can be attributed to slip along the Chocolate Mountains fault. However, considering that the muscovite data imply that final slip on the fault occurred prior to 48 Ma, it is evident that other factors such as structurally higher faults and/or erosional denudation were also involved. A minor exception to the above interpretation is indicated by the fact that muscovite ages of schist from the eastern margin of the dome tend to be slightly younger than those from the west. As already noted with regard to the biotite, we consider this to reflect relatively late, brittle reactivation of the Chocolate Mountains fault in the east.

Subsequent to ca. 44 Ma, cooling of both the schist and the gneiss abruptly slowed. Both units appear to have resided within the middle crust at depths appropriate for ~350 °C ambient conditions until ca. 28 Ma. During this period, biotites from slightly different structural depths appear to have closed at different times. As discussed above, biotite recrystallization may have been important, particularly in the eastern area. We believe that temperatures were sufficiently high, however, that the effect of recrystallization upon ⁴⁰Ar retention was not obvious, since neoformed green biotite and prograde red-brown biotite from equivalent areas yield similar age results (Fig. 4D; Table 2).

K-feldspars along the northern exposure of the Chocolate Mountains record a second phase of rapid cooling from ~350 °C to <150 °C from 28 to 24 Ma. We attribute this cooling primarily to slip on the Gatuna fault. The contrast in the biotite ages across the Chocolate Mountains fault in the eastern area could be explained by local reactivation of the fault during this
interval. After 24 Ma, continued cooling at a slower rate through the apatite partial annealing zone at 18–20 Ma may reflect upper crustal extension and/or erosional exhumation that ultimately exposed the metamorphic assemblage in Miocene time.

**DISCUSSION**

**Chocolate Mountains fault**

The first detailed analysis of the Vincent–Chocolate Mountains fault system was conducted by Ehlig (1958), who studied the Vincent thrust and Pelona Schist of the San Gabriel Mountains. This work led to four critical observations: (1) The Pelona Schist exhibits a single prograde metamorphism and associated deformational fabric. (2) Metamorphic grade increases structurally upward in the schist, ranging from lower greenschist facies at the base of the exposed section to upper greenschist facies adjacent to the upper plate. (3) Prefaulting igneous and amphibolite-facies metamorphic assemblages in the upper plate are retrograded to upper greenschist facies in a 1-km–thick mylonite zone at the base of the upper plate; i.e., there is a “metamorphic convergence” between schist and upper plate. (4) Fold axes and lineations in the mylonite zone are parallel to the single orientation of fold axes and lineations in the schist. From these relations, Ehlig (1958) concluded that the contact between schist and upper plate is a symmetamorphic thrust fault along which the schist was buried and metamorphosed (see also Ehlig, 1981; Jacobson, 1983a, 1983b, 1997).

For many years following the work of Ehlig (1958), other segments of the Vincent–Chocolate Mountains fault system were generally considered to have the same tectonic significance as the Vincent thrust (Ehlig, 1968; Harvill, 1969; Vargo, 1972; Haxel and Dillon, 1978). Beginning in the early to mid 1980s, however, it was realized that many of these faults developed after the prograde metamorphism of the schists (Frost et al., 1982; Haxel et al., 1985; Silver and Nourse, 1986; Postlethwaite and Jacobson, 1987; Jacobson et al., 1988). This is important for two reasons. First, the model involving formation of the schists in a SW-dipping subduction zone (Haxel and Dillon, 1978) rests almost entirely upon the assumption that top-to-NE movement on the Chocolate Mountains fault occurred during underthrusting of the schist. If the top-to-NE shear indicators have a different origin, then there is no compelling reason to retain this model, as it conflicts with other aspects of the geology of southern California and southwestern Arizona (Burchfield and Davis, 1981; Crowell, 1981; Dickinson, 1981; Hamilton, 1987, 1988). Second, the Pelona–Orocopia–Rand Schists underwent metamorphism at relatively great depths (25 to >30 km). Determining the origin of the faults that overlie the schists is fundamental to understanding when and how these rocks were returned to the surface.

The Chocolate Mountains fault in the Gavilan Hills was first studied as part of a regional geologic mapping project by Haxel (1977). He noted both the mylonitic nature of the fault and the general parallelism of lineation between the gneiss and nearby schist. By analogy with the Vincent thrust in the San Gabriel Mountains, Haxel (1977) concluded that the Chocolate Mountains fault was also a thrust fault. Subsequent structural studies by Simpson (1990) and Oyarzabal et al. (1997), however, and additional data presented here, indicate two key differences between the Vincent thrust and the Chocolate Mountains fault. First, the Pelona Schist in the San Gabriel Mountains contains only a single generation of lineation that displays no systematic variation in orientation with respect to distance from the Vincent thrust (Ehlig, 1958, 1981; Jacobson, 1983b). In contrast, the Orocopia Schist in the Gavilan Hills contains two distinct lineations. Only the one in the structurally highest part of the schist is parallel to that in the gneiss. Second, the metamorphic convergence associated with the Vincent thrust in the San Gabriel Mountains involves retrograde metamorphism in the upper plate, but prograde metamorphism in the underlying Pelona Schist (Ehlig, 1958, 1981; Jacobson, 1983a; 1997). Metamorphic convergence is also present along the Chocolate Mountains fault in the Gavilan Hills. In this area, however, it involves retrograde metamorphism of both the upper and lower plates. Furthermore, successively younger generations of fabrics along the Chocolate Mountains fault appear to have formed during progressively decreasing temperature. These differences are most easily explained if the Chocolate Mountains fault is an exhumation structure that has excised the original burial thrust. Our ⁴⁰Ar/³⁹Ar thermal history results (Fig. 8) indicate that movement along the Chocolate Mountains fault occurred during a phase of rapid cooling from <60–44. We consider that the Chocolate Mountains fault, itself, was responsible for a significant proportion of that cooling, but, as already noted, movement along structurally higher faults and/or erosion is also required.

The coincidence of muscovite ages between Orocopia Schist and gneiss indicates that movement on the Chocolate Mountains fault must have been essentially over by 48 Ma (notwithstanding the local brittle disruption along the east side of the dome). It is not proven, however, that all fabrics characteristic of the contact between Orocopia Schist and gneiss formed by this time. Because the schist and gneiss remained at temperatures of ~350 °C for an extended period following the early Tertiary phase of exhumation (Fig. 8), it is conceivable that cataclastic overprinting of the mylonites, and perhaps even some of the youngest, lowest-temperature mylonitization, could be much younger than 48 Ma.

The early Tertiary exhumation event inferred here, combined with the ca. 70 Ma maximum protolith age for the Orocopia Schist indicated by detrital zircons (Grove et al., 2000; Jacobson et al., 2000), suggests that the time span between initial underthrusting of the protolith of the Orocopia Schist and exhumation of the schist along the Chocolate Mountains fault may have been on the order of 10–20 m.y. This is consistent with petrographic observations described here and by Oyarza-
bal et al. (1997), which imply that the earliest exhumation structures formed while metamorphic temperatures were still relatively high. This also fits our observation that there is a complete continuum in style between the early and late lineations. Perhaps also relevant is the lack of strong reorientation of lineation in the schist adjacent to the central klippen of gneiss. As noted previously, the klippen are thought to preserve a deeper part of the upper plate than found along the margins of the Gavilan Hills dome, and may provide evidence of a gradual transition between burial and exhumation structures.

Our interpretation of a $<60$–48 Ma window for slip along the Chocolate Mountains fault has potentially important tectonic implications. In particular, this age assignment requires that the fault was active during Laramide subduction (Coney and Reynolds, 1977; Dickinson, 1981) and thus suggests the presence of low-angle denudational (i.e., normal) faults within an overall convergent-margin setting. Based on lithology and style of metamorphism, the Pelona–Orocopia–Rand Schists are commonly viewed as the remnants of a subduction complex marking the boundary between the North American and Farallon plates (Graham and England, 1976; Burchfiel and Davis, 1981; Crowell, 1981; Malin et al., 1995; Jacobson et al., 1996; Wood and Saleeby, 1997). If so, then exhumation along the Chocolate Mountains fault may have been driven by underplating of subducted material at the base of the schist complex, similar to mechanisms suggested for exhumation of the Franciscan Complex along the Coast Range fault (Cloos, 1982; Platt, 1986; Jayko et al., 1987). Alternatively, Hall (1991), Barth and Schneiderman (1996), and Saleeby (1997) proposed that the schists represent a part of the Great Valley forearc basin buried along an intraarc thrust. Although the forearc model involves formation of the schist within the overriding North American plate, rather than at its lower boundary, it does call upon low-angle subduction of the Farallon slab to explain convergence between the arc and forearc. Thus, even in this model, denudation along the Chocolate Mountains fault could still have ultimately been driven by subduction-underplating at depth.

**Gatuna fault**

The latest phase of movement on the Gatuna fault occurred under brittle conditions and resulted in juxtaposition of the Winterhaven Formation with the gneiss and, locally, Orocopia Schist (Figs. 2–4). This period of slip is presumed to have occurred in middle Tertiary time based on the rapid cooling of the Schist (Figs. 2–4). This period of slip is presumed to have occurred in middle Tertiary time based on the rapid cooling of the Schist (Figs. 2–4). This period of slip is presumed to have occurred in middle Tertiary time based on the rapid cooling of the Schist (Fig. 8). As indicated previously, however, Oyarzabal et al. (1997) observed that brittle deformatonal features along the Gatuna fault were superposed upon an older generation of mylonitic fabrics at the top of the gneiss. It is tempting to conclude that this initial ductile phase of movement coincided with the early Tertiary development of the Chocolate Mountains fault and thus accounted for part of the early phase of cooling of schist and gneiss. However, the mylonites along the Gatuna fault tend to resemble the relatively young, fine-grained mylonites along the Chocolate Mountains fault. As discussed in the previous section, we cannot exclude the possibility that the latter mylonites could be as young as ca. 28 Ma, the time at which the schist and gneiss began their ascent from midcrustal to shallow levels.

The observation of a ductile phase of slip on the Gatuna fault has implications for the structural evolution of the Winterhaven Formation. In particular, our study indicates that, despite the incomplete, low-grade nature of recrystallization, the Winterhaven Formation contains a pervasive metamorphic cleavage oblique to bedding and subparallel to late foliations in the gneiss and schist (Fig. 3A). The Winterhaven Formation also includes a lineation approximately parallel to that in the gneiss and uppermost Orocopia Schist, although the conformity is not nearly as strong as that between the gneiss and schist alone (Fig. 3B). Prograde metamorphic assemblages in the Winterhaven Formation clearly formed at much lower temperatures than those in the schist and gneiss, confirming that the Gatuna fault is a major structural discontinuity. The chlorite-zone metamorphism of the Winterhaven Formation is also relatively low grade compared to the conditions characterizing the early stages of exhumation of the Orocopia Schist, when Ti-rich biotite was stable. However, continued deformation of the schist was accompanied by declining temperatures, leading to the breakdown of medium-grade biotite to chlorite or low-temperature, Ti-poor biotite, similar to retrograde reactions exhibited by the gneiss. Hence, the gap in structural level between the low-grade fabric in the Winterhaven Formation and the latest stages of ductile deformation of the Orocopia Schist and gneiss need not be great. In other words, cleavage and lineation in the Winterhaven Formation and exhumation-related fabrics in the schist and gneiss could be genetically related. However, without thermochronologic data for the Winterhaven Formation, we cannot rule out the possibility that its lineation is an old fabric only coincidentally parallel to that in the schist and gneiss. More work is needed comparing the structural evolution of schist, gneiss, and Winterhaven Formation elsewhere in the Picacho-Peter Kane Mountain area (Fig. 2).

The Gatuna fault is broadly similar to the low-angle Sortan fault to the east, which also separates Winterhaven Formation from Orocopia Schist and gneiss (Fig. 2) (Haxel et al., 1985). The age of the Sortan fault is not well constrained. Haxel et al. (1985) considered that movement occurred prior to 60 Ma based on the inference that the fault was intruded by the “granite of Marcus Wash.” As noted above, however, the unit formerly designated the “granite of Marcus Wash” is now considered to belong to the upper plate of the Sortan fault. Based on the metamorphism and regional associations of the Winterhaven Formation, gneiss, and Orocopia Schist, Haxel et al. (1985) postulated removal of $\sim5$–10 km of crustal section along the Sortan fault. Our thermal history results, indicating $\sim200^\circ$C of cooling after 28 Ma (Fig. 8), are consistent with $\sim8$ km of structural excision due to slip along the Gatuna fault. Winterhaven Formation above the Sortan fault contains metamorphic
biotite (Haxel et al., 1985) and is thus somewhat higher grade than that in the Gavilan Hills. Thus, structural excision along the Gatuna fault might be expected to be greater than that along the Sortan fault.

Regional middle Tertiary relations

Our thermochronologic data are relevant to a debate regarding the age of middle Tertiary extension in the Picacho–Peter Kane Mountain and surrounding areas. The oldest Tertiary supracrustal rocks in this region include arkosic sandstone, sedimentary breccia, and conglomerate, which in most regions are only a few tens of meters thick (Olmsted et al., 1973; Dillon, 1976; Crowe, 1978; Eberly and Stanley, 1978; Sherrod and Tosdal, 1991; Lombard, 1993). Exceptions occur in the Laguna and Muggins Mountains, located 10–20 km south of the Trigo, Middle, and Castle Dome Mountains (Fig. 1), where arkosic sediments reach thicknesses of ~2 km. These sediments are locally in depositional contact with the Winterhaven Formation and upper plate of the Chocolate Mountains fault, although fault contacts are also common (Dillon, 1976; Grubensky and Bagby, 1990; Sherrod and Tosdal, 1991; Richard, 1993). Clasts of all locally exposed crystalline rocks are abundant in the sediments, except for ones derived from the Orocopia Schist, which have been reported from only two localities (Dillon, 1976; R.M. Tosdal, 1997, written commun.). The arkosic sediments are not dated directly, but are overlain by the Quechan volcanic rocks, which were most likely erupted at 26–28 Ma (Spencer et al., 1995). The Quechan volcanic rocks, which comprise flows and lesser volcaniclastic strata of dominantly intermediate composition, are overlain by felsic tuffs as young as 22 Ma. Extension and tilting of the supracrustal rocks occurred subsequent to eruption of the silicic tuffs, presumably coincident with detachment faulting in west-central to southeast Arizona (Spencer and Reynolds, 1989; Spencer et al., 1995). Disagreement exists, however, as to when middle Tertiary extension started. Some workers have reported that the Quechan volcanic rocks and felsic tuffs are conformable, leading to the conclusion that the main phase of middle Tertiary extension did not begin until after 22 Ma (Sherrod and Tosdal, 1991; Sherrod and Hughes, 1993). In contrast others have argued for an unconformity between the two units, implying that significant extension occurred during eruption of the Quechan volcanic rocks (Dillon, 1976; Drobeck et al., 1986). Our data, indicating rapid cooling of middle crustal rocks beginning at ca. 28 Ma (Fig. 8), support the latter interpretation. To a certain extent, previous workers have tended to downplay the significance of middle Tertiary extension prior to 22 Ma because of the absence of thick accumulations of synorogenic sediments of potentially appropriate age, other than in the Laguna and Muggins Mountains (Sherrod and Tosdal, 1991; Spencer et al., 1995). In this context, it is important to note that our thermochronologic data for denudation beginning at 28 Ma (Fig. 8) were obtained in an area where the basal arkosic sediments form a discontinuous sheet generally no more than a few tens of meters in thickness (Haxel, 1977). Hence, paucity of synorogenic sediments cannot be taken as evidence for lack of extension. Instead, the restricted nature of such deposits might simply reflect a combination of elevation and climate conditions that resulted in development of external drainages. Interestingly, the Pacific and North American plates first came into contact at ca. 28 Ma and at approximately the same latitude as the study area (Atwater, 1989).

It is puzzling that sediments beneath the Quechan volcanic rocks contain numerous clasts of gneiss and Winterhaven Formation, yet almost none of schist, as all three units are now in such close spatial association. The oldest sediment to contain abundant schist detritus is a Miocene fanglomerate that is widespread throughout the Picacho–Peter Kane Mountain area (Fig. 2) (Sherrod and Tosdal, 1991; Hughes, 1993). The fanglomerate rests depositionally upon the felsic tuffs and is only mildly tilted. The late exposure of schist compared to gneiss and Winterhaven Formation might be taken as evidence that the Chocolate Mountains Fault is much younger than we infer, which would allow the schist to have remained at relatively deep levels even after the upper plate and Winterhaven Formation were at the surface shedding debris into the pre-Quechan basins. However, we find this possibility difficult to reconcile with the $^{39}$Ar/ $^{39}$Ar ages suggesting that the schist and gneiss have been in close proximity since at least 48 Ma. Instead, we propose that the schist was brought close to the surface during the exhumation event that began at 28 Ma, but that eruption of the 1–2 km thickness of Quechan and younger volcanic rocks delayed its ultimate exposure until following the reactivation of extension after 22 Ma. At least in the Gavilan Hills, final breaching of schist did not occur until after 18.7 Ma, as indicated by apatite fission track ages (Fig. 8) (Oyarzabal et al., 1997). Furthermore, similar fission track ages from the gneiss of the Gavilan Hills indicate that this particular body could not have been a source of detritus for the sub-Quechan sediments.

Although not shown in detail in Figure 2, middle Tertiary extension resulted in the development of a complex array of fault systems within the upper Oligocene to lower Miocene volcanic and sedimentary rocks. In general, these faults do not significantly cut the Orocopia Schist and gneiss. We suspect that the high degree of brittle disruption observed throughout the Winterhaven Formation reflects the role of this unit as a zone of accommodation between the differently deforming supracrustal and crystalline rocks.

Regional distribution and orientation of the late lineation

An intriguing finding of this study is the marked variation in trend of late lineation in both schist and gneiss along the length of the Chocolate Mountains fault within the Gavilan Hills (Fig. 3B). Previous studies have emphasized only the western segment of the fault, where the lineation trends approximately NE-SW and sense of movement is approximately top-to-NE (Haxel, 1977; Dillon et al., 1990; Simpson, 1990).
In contrast, we found that the average trend of the late lineation for the Gavilan Hills as a whole is essentially E–W.

To investigate the region-wide extent and orientation of the late lineation, we compared our data from the Orocopia Schist (Fig. 3B) to measurements from the schist collected by Haxel (1977) in the Picacho–Peter Kane Mountain area and Dillon (1976) in the southern Chocolate Mountains (Fig. 1). A stereonet plot of our data from the Gavilan Hills (Fig. 9) clearly shows the late lineations with E–W to WNW–ESE trend, although most measurements do, in fact, trend approximately NE–SW. In part, this reflects the fact that the difference in trend between the early and late lineations along the westernmost Chocolate Mountains fault in the Gavilan Hills is not great (Fig. 3B).

Furthermore, even where the contrast in orientation between the two lineations is large, the late lineation is generally restricted to a relatively narrow zone adjacent to the fault (Fig. 3B). Thus, areally uniform sampling of the schist strongly emphasizes the early lineation, which partly explains why the two separate fabrics were not recognized previously.

Lineation measurements of Haxel (1997), which were obtained from all the schist bodies of Figure 2 except the one in the Trigo Mountains of Arizona, show the same spread in orientation as our data from the Gavilan Hills alone (Fig. 9). Haxel (1977) noted that many of the approximately E–W trending lineations in his data set came from the Ferguson Lake schist area. Haxel (1977) considered that these E–W orientations resulted from postmetamorphic rotation of originally NE–SW trends due to intrusion of the “granite of Marcus Wash.” As noted above, however, this unit is now known to be in structural contact with the schist along the Sortan fault, suggesting that the E–W lineations are fault-related.

As with our measurements and those of Haxel (1977), lineations from the southern Chocolate Mountains (Dillon, 1976) exhibit a large spread in orientation, and include a significant population with approximately E–W trend (Fig. 9). However, a very high proportion of measurements from the southern Chocolate Mountains trend approximately N–S to NNW–SSE, compared to the dominant NE–SW trend in the Picacho–Peter Kane Mountain area. This difference was previously noted by Dillon et al. (1990), who considered whether it might be related to differential Neogene vertical-axis rotations associated with dextral shear on the San Andreas fault system (cf. Luyendyk et al., 1985). Although Dillon et al. (1990) ultimately discounted this possibility, they proposed no alternative explanation. One possibility is that prograde lineations in the two areas had different orientations from the outset, due to strain heterogeneities during underthrusting. On the other hand, if early lineations initially had a uniform orientation, then differential rotation is required during exhumation. In this case, the average trend in southern Chocolate Mountains may be most indicative of the original orientation, as this area preserves a greater thickness of upper plate than the Picacho–Peter Kane Mountain area (Dillon, 1976; Haxel, 1977), which could indicate less extensive overprinting of the prograde fabric. An implication of the above scenario is that even schist relatively deep in the section in the Picacho–Peter Kane Mountain area may have undergone some degree of reorientation of lineation during exhumation.

Although more work is needed, we suggest from the above analysis that the average direction of extension associated with the Chocolate Mountains fault may be approximately E–W, rather than NE–SW as emphasized previously. This orientation is interesting in light of the regional-scale E–W structural grain associated with the Chocolate Mountains anticlinorium. In part, this grain is defined by the E–W alignment of the individual schist bodies extending from the Gavilan Hills eastward into southwest Arizona (Fig. 1). In detail, it is reflected in the E–W elongated shapes of individual culminations such as those underlying the Gavilan Hills and the area between Little Picacho Wash and White Wash (Fig. 2). Even the NW-SE–elongated belt of schist in the southern Chocolate Mountains is defined by an en echelon arrangement of individual culminations elongated approximately E–W (Fig. 1). The combined Trigo Mountains–Ferguson Lake schist body counters this trend in being elongated N–S (Fig. 2). However, the eastern margin of this body is truncated by a young high-angle fault (Fig. 2), so the original shape is unknown (the same is true for the Peter Kane Mountain body of schist). Furthermore, large E–W folds are clearly defined along the west side of this schist body by the outcrop pattern of the Sortan fault and, in detail, by the patterns of the Winterhaven Formation and Jurassic metavolcanic rocks above the fault (Fig. 2). These relations suggest either that growth of the Chocolate Mountains anticlinorium...
began in early Tertiary time, or that early Tertiary strain patterns (i.e., the E–W lineation) exerted an influence on development of the anticlinorium at a later date. Tilt patterns and facies relations of the upper Oligocene to lower Miocene sedimentary and volcanic units imply at least some growth of this structure during middle Tertiary time (Richard, 1989; Grubensky and Bagby, 1990; Sherrod and Tosdal, 1991).

CONCLUSIONS

The Chocolate Mountains fault in the Gavilan Hills area of southeasternmost California was initially interpreted as a thrust fault responsible for prograde metamorphism of the Orocopia Schist, analogous to the Vincent thrust of the San Gabriel Mountains. Subsequent studies by Simpson (1990) and Oyarzabal et al. (1997), and new results presented here, demonstrate instead that it is a retrograde structure associated with exhumation of the schist. Muscovite and hornblende \(^{40}\text{Ar}/^{39}\text{Ar}\) ages imply that movement on the Chocolate Mountains fault occurred between <60–48 Ma; i.e., the fault is Laramide in age. The retrograde nature of the Chocolate Mountains fault indicates that its top-to-NE to top-to-East transport direction has no bearing on the burial history of the Orocopia Schist. Sense of movement on the burial thrust is nowhere constrained directly, but, based on regional considerations, was most likely top-to-W or -SW (Yeats, 1968; Crowell, 1968, 1981; Burchfiel and Davis, 1981; Dickinson, 1981; Hamilton, 1987, 1988; Malin et al., 1995; Jacobson et al., 1996).

The Chocolate Mountains fault shows a close spatial association with the Gatuna fault. Early workers considered the Gatuna fault to be a steeply dipping structure, but map patterns provide evidence that, on a regional scale, it is likely subhorizontal. Mylonites in gneiss adjacent to both the Gatuna and Chocolate Mountains faults exhibit similar textures and orientation of lineation. This may indicate an early Tertiary phase of movement on the Gatuna fault related to slip on the Chocolate Mountains fault. Nonetheless, \(^{40}\text{Ar}/^{39}\text{Ar}\) thermochronology of biotite and K-feldspar suggest that the main phase of slip on the Gatuna fault occurred at ca. 28–24 Ma. The Gatuna fault occupies a similar structural position as the undated Sortan fault to the east.

Exhumation in the Gavilan Hills at 28–24 Ma presumably transported the Orocopia Schist and gneiss from midcrustal to shallow levels. Indeed, extension at this time apparently resulted in widespread exposure of gneiss in the Picacho–Peter Kane Mountain and surrounding areas, although not in the Gavilan Hills area, itself. Exposure of gneiss in the Gavilan Hills, and Orocopia Schist, in general, did not occur until following additional middle Tertiary extension subsequent to 22 Ma.

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