Tectonic Setting and Lithology of the Winterhaven Formation: A New Mesozoic Stratigraphic Unit in Southeasternmost California and Southwestern Arizona

U.S. GEOLOGICAL SURVEY BULLETIN 1599

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Tectonic Setting and Lithology of the Winterhaven Formation: A New Mesozoic Stratigraphic Unit in Southeasternmost California and Southwestern Arizona

By Gordon B. Haxel, Richard M. Tosdal, *and* John T. Dillon[1]

Abstract

A 450-m-thick sequence of distinctive, variably metamorphosed Jurassic(?) supracrustal rocks in southeasternmost California and southwesternmost Arizona is herein named the Winterhaven Formation. The formation consists of a basal dacite member, which evidently rests depositionally on and interfingers with Jurassic rhyodacitic metavolcanic rocks, a medial quartz arenite member, and an upper argillitic siltstone member. The formation is unconformably overlain by Tertiary rocks. Complex relations of the Winterhaven Formation to the late Mesozoic Orocopia Schist and overlying Chocolate Mountains thrust represent the superimposed effects of several late Mesozoic to late Tertiary deformational episodes. Significant lithologic contrasts indicate that the Winterhaven Formation is not related to the protolith of the Orocopia Schist. The Winterhaven Formation evidently was originally part of the upper plate of the Chocolate Mountains thrust and was subsequently placed directly over the Orocopia Schist along the Sortan fault, a newly recognized late Mesozoic low-angle normal fault. Because this juxtaposition and later metamorphism and intrusion by granite occurred before about 60 m.y. ago, the metamorphic age of the Orocopia Schist must be no younger than Late Cretaceous, rather than early Tertiary. The Winterhaven Formation has several similarities to, and may correlate with, the lower part of the Jurassic and (or) Cretaceous McCoy Mountains Formation.

INTRODUCTION

Geologic mapping and reconnaissance in southeastern California and southwestern Arizona from 1972 to 1985 have revealed a distinctive and widespread but previously unrecognized Mesozoic, probably Jurassic, lithostratigraphic unit (fig. 1). This sequence of siliciclastic sedimentary rocks, with a basal volcanic unit, is here named the Winterhaven Formation. The formation is important as part of the Mesozoic supracrustal record and because of its relations to the enigmatic Orocopia Schist.

[1]Alaska Division of Geological and Geophysical Surveys.

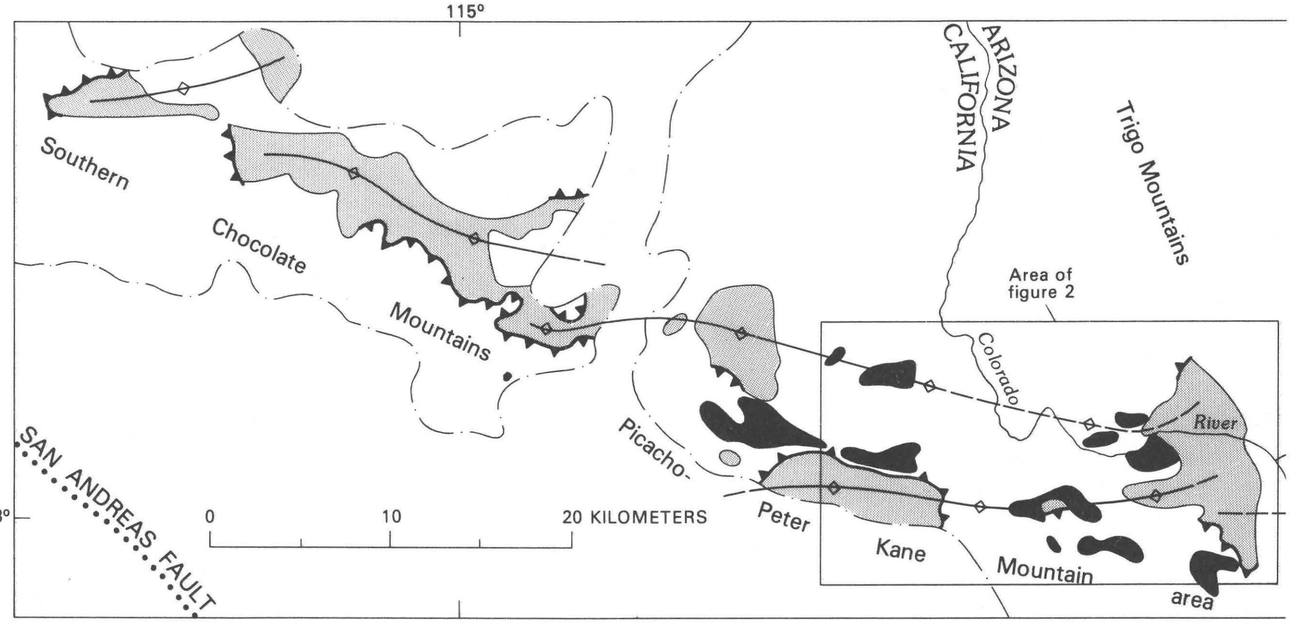
Elucidating the Mesozoic tectonic history of the region in the southeast corner of California and southwest corner of Arizona is substantially a matter of determining the temporal and tectonic relations among several major Mesozoic supracrustal lithostratigraphic units (Crowell, 1981). These units are: (1) The late Mesozoic Orocopia Schist, composed of thoroughly metamorphosed graywacke and minor basalt, mudstone, chert, and peridotite (Haxel and Dillon, 1978); (2) the Jurassic and (or) Cretaceous McCoy Mountains Formation of Harding and Coney (1985), a 7-km-thick continental clastic sedimentary sequence; (3) Jurassic and Jurassic(?) silicic and subordinate intermediate volcanic and hypabyssal rocks (Tosdal, 1982); and (4) the Jurassic(?) Winterhaven Formation and similar strata.

The purpose of this report is to summarize the extent and lithology of the Winterhaven Formation and to describe and discuss its relations to other Mesozoic lithotectonic units, particularly the Orocopia Schist. Most of the information presented here was gathered during mapping of the Picacho-Peter Kane Mountain area of southeasternmost California (fig. 2) as part of a study of the Orocopia Schist and related Chocolate Mountains thrust fault (Haxel, 1977), and during later mapping of the adjoining area to the north by R.M. Tosdal and D.R. Sherrod (unpub. data, 1982-85). The stratigraphy and sedimentary petrology of the Winterhaven Formation have yet to be studied in detail. The formation is named after a small California town just north of Yuma, Ariz.

Previous mention of some of the rocks here assigned to the Winterhaven Formation is restricted to brief descriptions by Olmsted and others (1973, p. 32) and Morton (1977, p. 16); in both of these reports, the rocks are tentatively correlated with the McCoy Mountains Formation. The name Winterhaven Formation was first used informally by Haxel (1977, app. 2).

ACKNOWLEDGMENTS

The presence in the Picacho area of supracrustal rocks intermediate in metamorphic grade between the Orocopia Schist and the middle Tertiary volcanic and sedimentary rocks was first pointed out to us by John Crowell and Perry Ehlig, both of whom have been of considerable help in our efforts to understand the Winterhaven Formation. We have also benefited from discussions with Bill Bagby, Peter Coney, Bruce



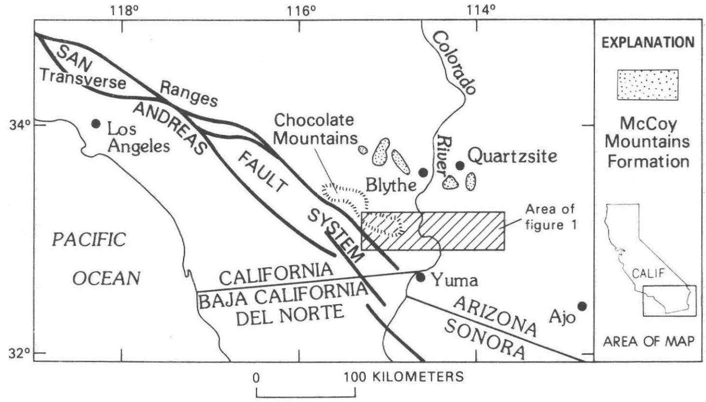
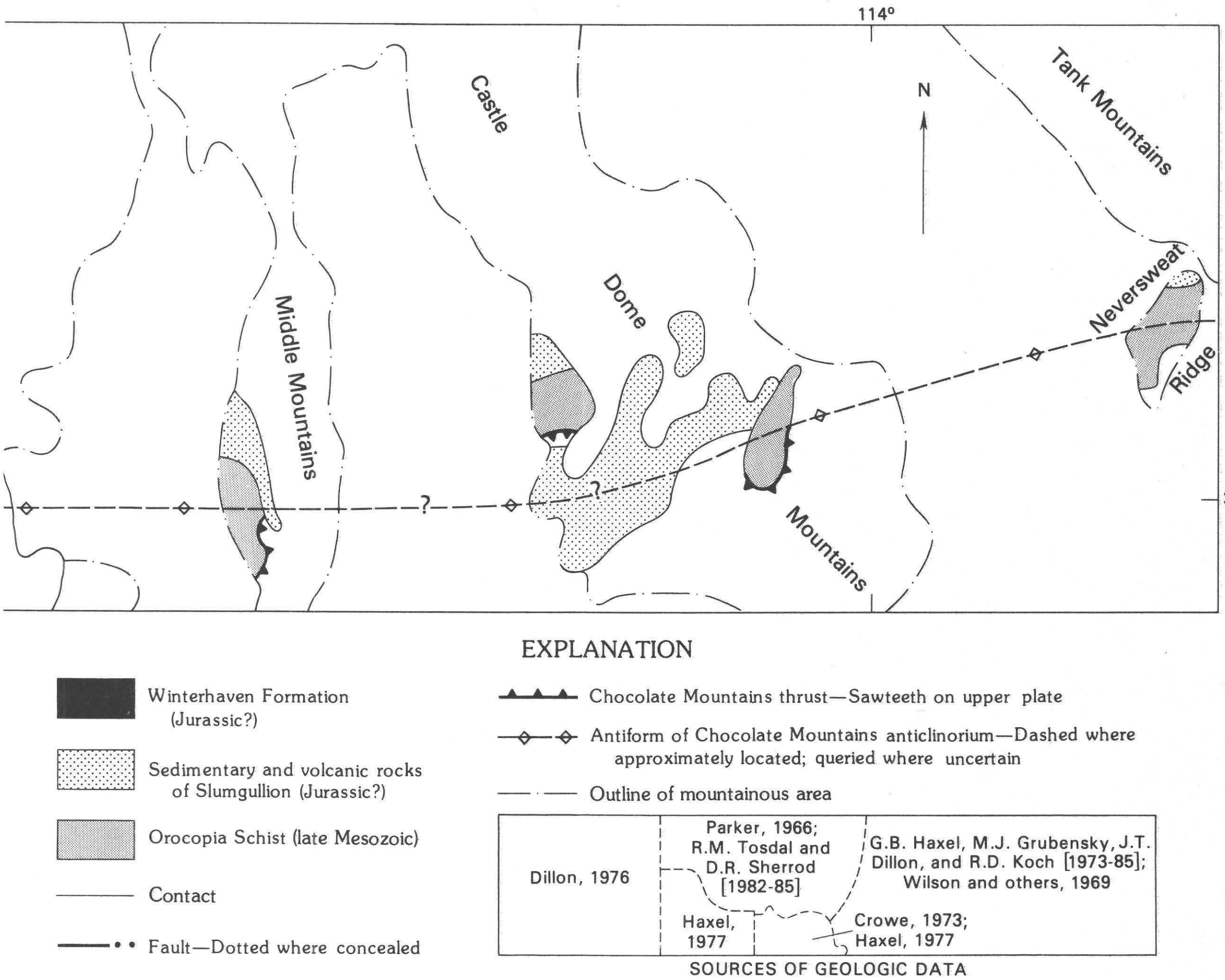


Figure 1. Distribution of the Winterhaven Formation, the Orocopia Schist, and the Chocolate Mountains thrust along the Chocolate Mountains anticlinorium in southeastern California and southwestern Arizona. Strata similar to the Winterhaven Formation in southwestern Arizona east of the Trigo Mountains are informally designated as the sedimentary and volcanic rocks of Slumgullion. Complex map relations among the Orocopia



Schist, Chocolate Mountains thrust, and Winterhaven Formation cannot be portrayed at this scale (see figs. 2, 3, 7, 8). Inset map shows location of map area and of outcrop area of the McCoy Mountains Formation of Harding and Coney (1985). In "Sources of Geologic Data," dates in brackets refer to unpublished mapping and (or) reconnaissance.

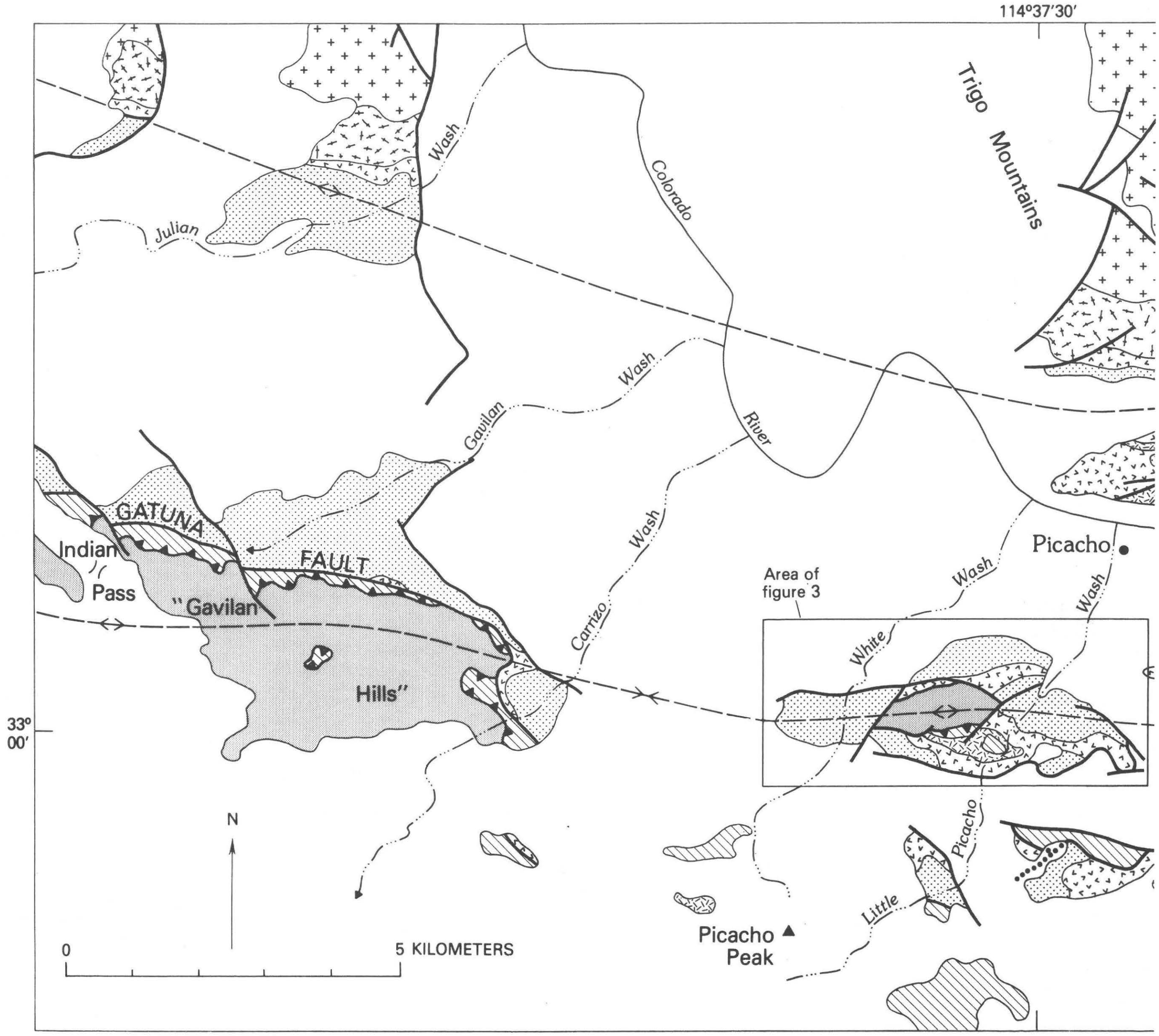
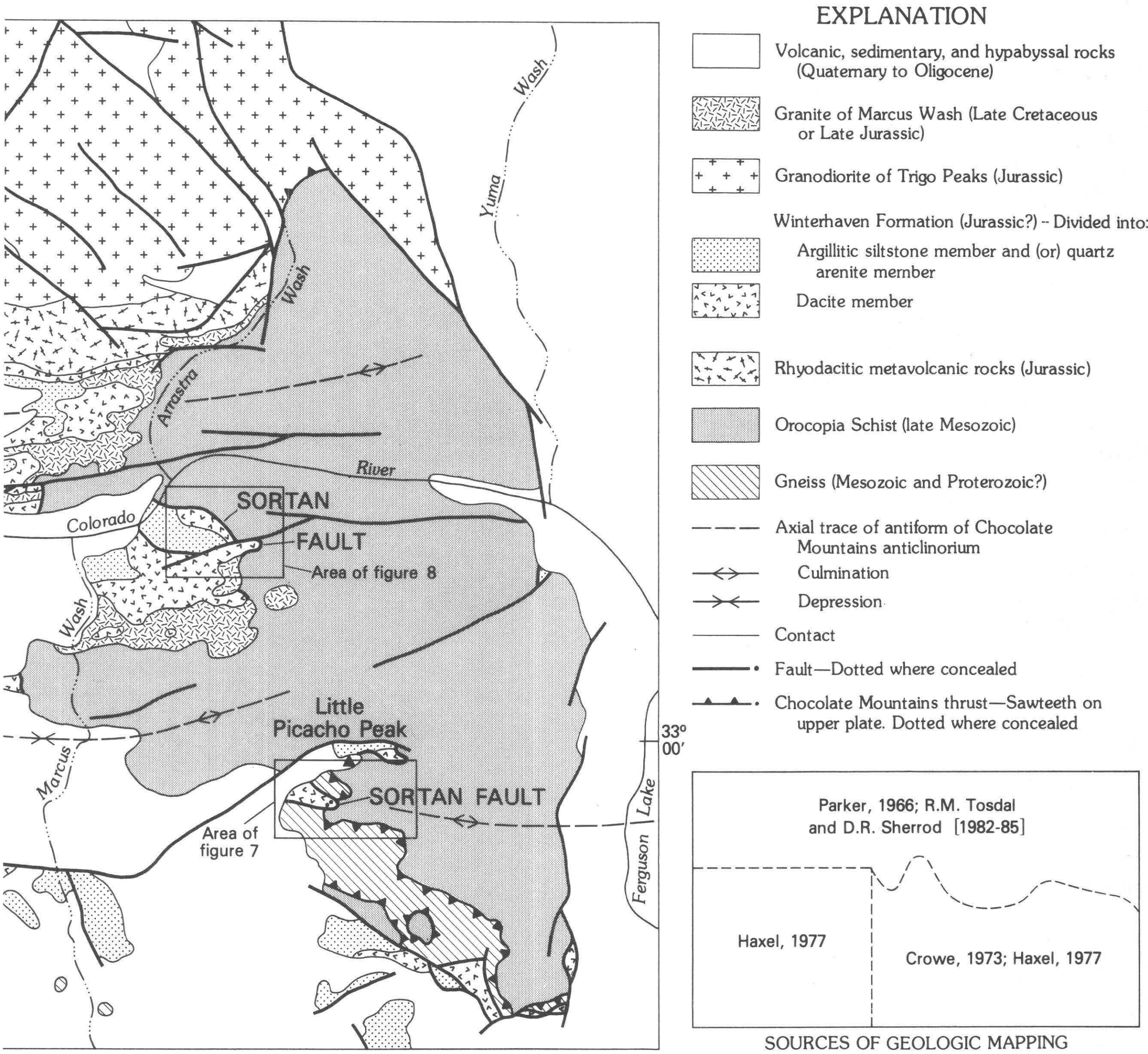


Figure 2. Pre-middle Tertiary rocks in the area between Indian Pass and Ferguson Lake, and Julian Wash and Arrastra Wash areas, southeastern California and southwestern Arizona (see fig. 1 for location). The granite of Marcus Wash may locally include some unmapped bodies of rhyodacitic metavolcanic rocks. "Gavilan Hills" is an



informal name used to designate the hills south of the Gatuna fault between Carrizo Wash and Indian Pass. Picacho is headquarters of the Picacho State Recreation Area. In "Sources of Geologic Mapping," dates in brackets refer to unpublished mapping.

Crowe, Bill Dickinson, Eric Frost, Mike Grubensky, Lucy Harding, Keith Howard, Carl Jacobson, Richard Koch, Donna Martin, Dan May, Frank Olmsted, Gary Pelka, Bob Powell, Lee Silver, and Paul Stone; and from the cooperation of the personnel of Picacho State Recreation Area. Much of this work was supported by U.S. National Science Foundation Grants EAR 71-00498 (Crowell) and EAR 81-15730 (Crowell).

GEOLOGIC SETTING

The dominant late Mesozoic tectonic feature of the Picacho-Peter Kane Mountain area and adjacent southern Chocolate Mountains (Dillon, 1976) is the Chocolate Mountains thrust, along which Mesozoic (and Proterozoic?) gneissic and granitoid rocks overlie the late Mesozoic Orocopia Schist. This regional thrust fault is exposed on the flanks, and the Orocopia Schist in the core, of the Tertiary Chocolate Mountains anticlinorium, which extends some 110 km from the central Chocolate Mountains east to Neversweat Ridge (fig. 1). This narrow, complexly faulted anticlinorium consists of several aligned, subparallel, or echelon antiformal segments.

Two subparallel east-trending antiforms control the distribution of exposures of the Winterhaven Formation and the Orocopia Schist within the Picacho-Peter Kane Mountain area and adjoining areas. The southern antiform extends from the area west of Indian Pass eastward toward Ferguson Lake; three separate exposures of the Orocopia Schist, overlain by segments of the Chocolate Mountains thrust, mark three culminations along the antiformal trace (fig. 2). The Winterhaven Formation is exposed along the flanks of the antiform and on the noses of the culminations. The northern antiform, likewise marked by culminations exposing the Orocopia Schist and (or) the Winterhaven Formation, extends from the easternmost southern Chocolate Mountains eastward through Peter Kane Mountain and the Julian Wash area to the southern Trigo Mountains. This antiform is disrupted by numerous high- to low-angle Tertiary faults and is less clearly defined than the southern antiform. In several areas along these antiforms, the Winterhaven Formation is folded into smaller, open to tight anticlines and synclines with wavelengths of about 0.5 to 1 km; both late Mesozoic and middle Tertiary folds are present.

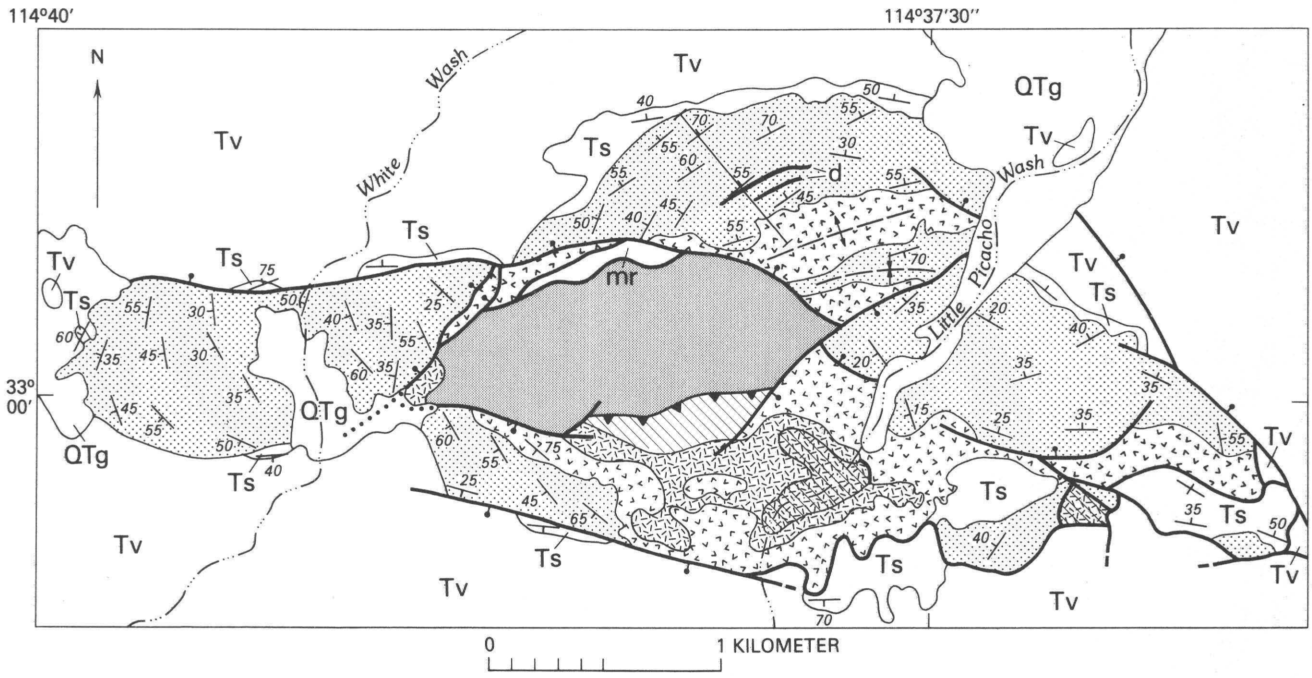
In most areas, the basal contact of the Winterhaven Formation is, or evidently was, a newly recognized late Mesozoic low-angle normal fault along which the Winterhaven Formation overlies both plates of the Chocolate Mountains thrust. Field relations in a few areas indicate that at its base the Winterhaven Formation originally stratigraphically overlaid Jurassic(?) rhyodacitic volcanic rocks that form part of the upper plate of the Chocolate Mountains thrust. In most places, these two types of Mesozoic basal contacts of the Winterhaven Formation have been modified or excised by Tertiary faults. The Winterhaven Formation is intruded by the epizonal granite of Marcus Wash (fig. 2). This granite is younger than the 163-m.y. (Middle or Late Jurassic) minimum protolith age and maximum metamorphic age of the Orocopia Schist (Mukasa and others, 1984), which it also intrudes, and older than earliest Tertiary K-Ar minimum ages of about 60 m.y. (Frost and Martin, 1983). The granite of Marcus Wash is considered to be either Late Jurassic or Late Cretaceous because igneous rocks of both these ages are common in the southeastern California-southwestern Arizona region. The Winterhaven Formation is overlain with angular unconformity by Oligocene to Holocene volcanic and sedimentary rocks (Crowe, 1973; Dillon, 1976; Crowe and others, 1979).

STRATIGRAPHY AND LITHOLOGY

The thickest section of known stratigraphic position is designated as the type section of the Winterhaven Formation (fig. 3). This section, which forms the northern limb of an anticline just west of Little Picacho Wash (in the southeast corner of the Picacho SW 7-1/2-minute quadrangle), consists of three members, with a total exposed thickness of about 450 m (fig. 4). Except where strongly metamorphosed, most of the Winterhaven Formation is typically dull purplish gray in outcrop.

The basal unit of the Winterhaven Formation is a dacite member, somewhat more than 80 m thick as presently exposed, composed of massive, purple and dark-brown, strongly altered, aphanitic to sparsely porphyritic rocks of intermediate composition, probably dacite and possibly including some andesite. Phenocrysts of plagioclase, biotite, and (or) another mafic mineral were originally present; the plagioclase and biotite are now completely altered to chlorite, sericite (that is, fine-grained white mica), and opaque minerals. These rather nondescript rocks presumably are largely volcanic flows. Rare beds of coarse-grained volcaniclastic graywacke are interlayered with the volcanic rocks. Near the top of the dacite member, some rocks contain amygdules of quartz or calcite, and there are some layers of dark-gray, very poorly bedded breccia composed of angular fragments (typically approx. 1-3 cm across) of strongly altered, sparsely porphyritic volcanic rock in a matrix of fine-grained sericitic sandstone. Locally this breccia forms a distinct layer, as much as 10 m thick, at the top of the dacite member. The dacite member also includes a few dikes and small, irregular, probably intrusive bodies of grayish-purple porphyry containing epidotized plagioclase laths, as much as 1 cm long, in a groundmass similar to that of the dacitic flows.

The middle unit of the Winterhaven Formation is a quartz arenite member (fig. 5), approximately 60 m thick, consisting chiefly of brown, tan, or white quartz arenite and feldspathic quartz arenite, some of which is slightly sericitic and (or) calcareous. The sandstone is very well indurated, fine to coarse grained (mostly medium grained), and laminated through medium bedded to locally massive. Subordinate rock types interbedded with the quartz arenite are brown sandy limestone, purplish-gray to brown argillitic siltstone, and brown to light-gray, thinly laminated, silty calcareous argillite, which in some places is converted to flaggy phyllite or semischist. At the base of the quartz arenite member, as much as a few meters of



EXPLANATION

- **QTg** — Gravel and conglomerate (Quaternary to Miocene)
- **Tv** — Volcanic rocks (Miocene and Oligocene)
- **Ts** — Sedimentary rocks (Oligocene)—Conglomerate, sandstone, and tuff
- **mr** — Mixed rocks—Metamorphosed Winterhaven Formation, and subordinate Orocopia Schist, intruded and severely hydrothermally altered by the granite of Marcus Wash
- Granite of Marcus Wash (Late Cretaceous or Late Jurassic)
- **d** — Hornblende diorite dikes (Cretaceous or Jurassic)
- Winterhaven Formation (Jurassic?)—Divided into:
  - Argillitic siltstone member and (or) quartz arenite member
  - Dacite member
- Orocopia Schist (late Mesozoic)
- Gneiss (Mesozoic or Proterozoic)
- Type section of Winterhaven Formation
- Contact
- Fault—Dashed where approximately located; dotted where concealed. Ball and bar on downthrown side
- Chocolate Mountains thrust—Sawteeth on upper plate
- Axial trace of anticline
- Axial trace of syncline
- Strike and dip of bedding
  - 55 Inclined
  - Vertical

Figure 3. Relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust in the area between Little Picacho Wash and White Wash (from Haxel, 1977, app. 2). See figure 2 for location. Fault-bounded sliver labeled "mr" (mixed rocks) northwest of center of map consists of metasedimentary and metavolcanic rocks of the Winterhaven Formation and subordinate Orocopia Schist, all intruded and severely hydrothermally altered by the granite of Marcus Wash; several faults within this sliver are not shown. Area southeast of map center that consists of gneiss strongly intruded by the granite of Marcus Wash is shown by superposition of patterns for these two units. Some pre-Tertiary contacts between the gneiss, the Winterhaven Formation, and the granite of Marcus Wash in the southeastern part of the map area have been modified or overprinted by Tertiary low-angle normal faults. Distribution of map units Ts and Tv is largely from Crowe (1973).

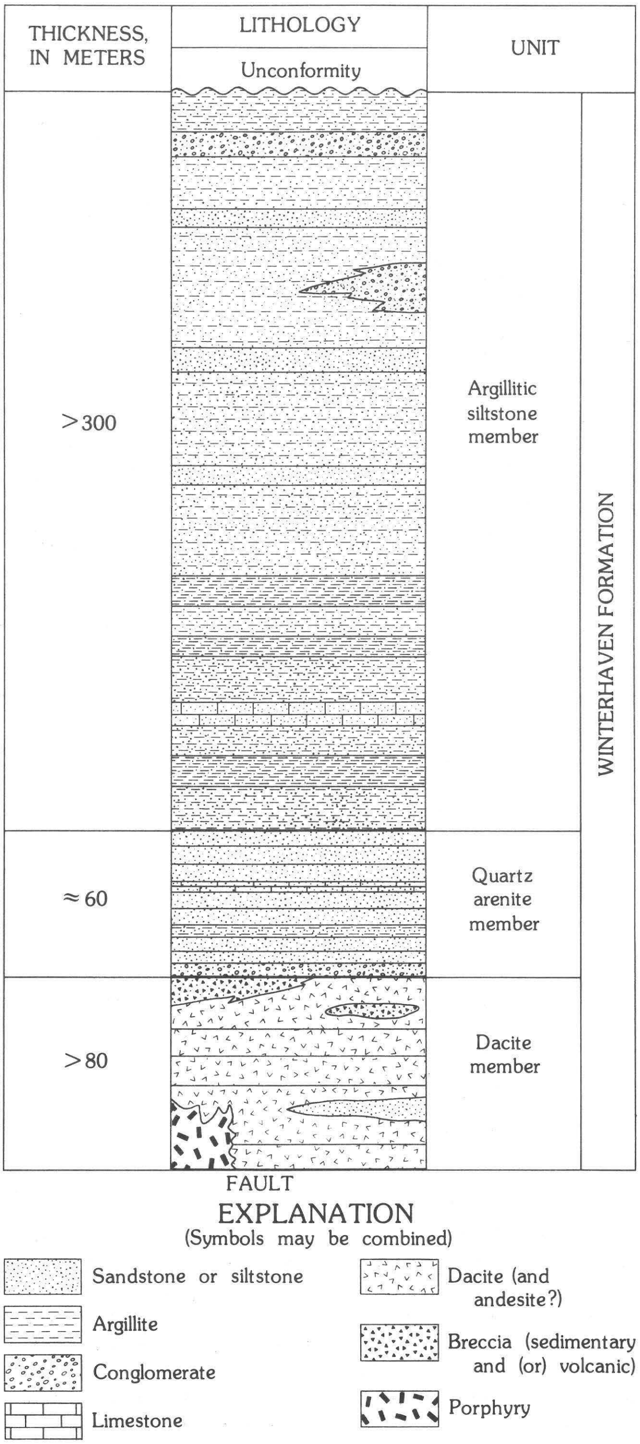


Figure 4. Generalized stratigraphic column for type section of the Winterhaven Formation (see fig. 3 for location). Position and thickness of individual lithologic layers within each of the three major units is schematic only. See text for lithologic descriptions.

brown and purple pebble conglomerate and conglomeratic sandstone are present; in some places these beds are absent, owing to minor faulting localized along the top of the dacite member.

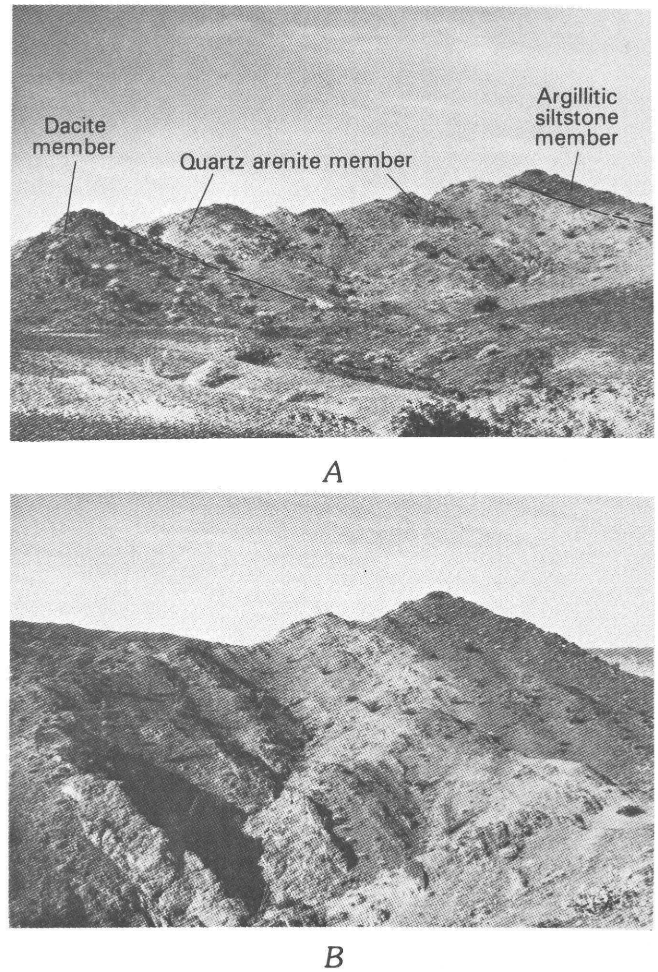


Figure 5. Strata of the Winterhaven Formation, on a ridge about 250 m north-northeast of south end of type section (fig. 3). Both views are approximately westward. A, Upper part of dacite member overlain by quartz arenite member, in turn overlain by base of argillitic siltstone member. Width of view, about 120 m. B, Upper part of quartz arenite member (right side of A); resistant beds of quartz arenite are interbedded with less resistant siltstone, argillite, and limestone. Dark unit capping sequence is base of the argillitic siltstone member, intruded by a hornblende diorite dike (fig. 3).

The quartz arenite member is overlain by an argillitic siltstone member, which in the type section has a maximum exposed thickness of about 300 m. The most common rock type is massive, dark-purple to dark-brown, slightly calcareous argillitic siltstone (micrograywacke), some of which is slightly sandy and some of which contains brown, decimeter-size, discoid calcareous concretions(?). Other abundant rock types are dark-purple and dark-brown silty argillite and brown to gray, medium-grained to very coarse grained, locally pebbly, slightly calcareous graywacke. Relatively minor rock types are dark-purple argillite, dark-brown sandy limestone, tan, slightly argillitic sandstone, and granule to pebble conglomerate with a graywacke matrix. The member as a whole coarsens upward; several rock types coarsen toward the top of the exposed section; and the coarser grained rock types, notably conglomerate, are more common toward the top.

The most common clasts in the conglomerates of the Winterhaven Formation are well-rounded to very well rounded pebbles, typically about 0.5 to 3 cm in diameter, of black, white, brown, and dark-bluish-gray chert or very fine grained quartzite; a few of these pebbles are faintly laminated. Also common are well-rounded clasts, typically 2 to 5 cm in diameter but locally as much as 10 cm in diameter, of fine-grained, vitreous, white or light-gray quartzite. A few conglomerate beds also contain intraformational clasts of purple and brown graywacke, argillite, and siltstone; these large pebbles and small cobbles are typically subrounded to rounded. Small, pebble-size "shale chips" are locally present along bedding planes. Pebbles of dull-red-brown or light-gray, finely porphyritic volcanic rocks and fine-grained, nondescript granitic rocks are rare. No clasts of Orocopia Schist or of gneissic rocks were found, and these are believed to be absent.

All exposures of the Winterhaven Formation within the Picacho-Peter Kane Mountain area and the adjoining area to the north (fig. 2) are lithologically similar to some part of the type section. A 500- or 600-m-thick homoclinal section along Marcus Wash about 4 km southwest of Little Picacho Peak is lithologically similar to the argillitic siltstone member of the type section but has not been correlated with it in detail because of the absence of distinctive marker units in either section. In the area between Carrizo Wash and Gavilan Wash, the quartz arenite member is less than 10 m thick and in most places absent, so that the argillitic siltstone member rests directly on the dacite member.

DISTRIBUTION IN OUTLYING AREAS OF CALIFORNIA; SIMILAR STRATA IN SOUTHWESTERN ARIZONA

Northwest of Indian Pass, the Winterhaven Formation is in part poorly exposed beneath a cover of basalt-boulder talus and has been examined in less detail than farther east. In the southern Chocolate Mountains (fig. 1), rocks similar to the Winterhaven Formation are restricted to a few localized outcrops at the southeast end of the range (Dillon, 1976, p. 203). Strata equivalent to the Winterhaven Formation have not been recognized in the main part of the Chocolate Mountains (fig. 1) nor west of the San Andreas fault. The only other strata similar to the Winterhaven Formation known in California occur within a fault-bounded block in low hills west of the Imperial Dam, 9 km south of Ferguson Lake (fig. 2).

Strata lithologically similar to the Winterhaven Formation are exposed in a large area of the southern Castle Dome Mountains, and in smaller areas in the Middle Mountains and at the north end of Neversweat Ridge (fig. 1). These strata are here referred to as the sedimentary and volcanic rocks of Slumgullion (after Slumgullion Pass in the Castle Dome Mountains). In the southern Castle Dome Mountains, the Slumgullion unit is considerably thicker and more diverse than the Winterhaven Formation (fig. 6). In particular, the Slumgullion unit contains large amounts of rhyodacitic volcanic rocks and coarse conglomerate and sedimentary breccia, rock types that are absent from the Winterhaven Formation. Nonetheless, the Slumgullion section includes lithologic units that are similar to, and occur in the same stratigraphic order as, the three members of the Winterhaven Formation. Provisional lithologic correlations between the Winterhaven Formation and the Slumgullion unit are shown in figure 6; confirmation of these correlations awaits completion of studies in progress of the Slumgullion unit.

METAMORPHISM AND DEFORMATION

The Winterhaven Formation is incipiently to strongly recrystallized, but over much of its outcrop area, mainly along the southern (Indian Pass to Ferguson Lake) antiform, it is not penetratively deformed. Sedimentary rocks in these areas are typically quartzitic or argillitic and show well-preserved sand and silt grains in thin section. The volcanic rocks recrystallized more readily and in some places have been converted to massive, very fine grained granofels composed of relict plagioclase laths (partially to completely altered to epidote and (or) sericite), epidote, chlorite, biotite, opaque minerals, calcite, and sericite, with or without sparse quartz or actinolite.

In the area of Arrastra Wash and lower Marcus Wash (fig. 2), where the Winterhaven Formation is intruded by the granite of Marcus Wash, deformation and metamorphism are more intense. The dacite member has been converted to greenschist-facies schist or hornfelsic granofels, both composed of chlorite and (or) biotite, actinolite, epidote, albite, and quartz; relict plagioclase laths are uncommon. The metasedimentary rocks overlying the dacite member have been converted to quartzofeldspathic phyllite, semischist, and schist containing metamorphic muscovite, biotite, epidote, chlorite, and calcite. The Winterhaven Formation in the Julian Wash area is intermediate in textural and mineralogic metamorphic grade between the generally undeformed rocks along the southern antiform and the more or less schistose rocks of the Arrastra Wash-Marcus Wash area.

In both the Arrastra Wash and Julian Wash areas, the Winterhaven Formation is folded into a south-facing, shallowly plunging, asymmetric syncline with a steep to slightly overturned northern limb and subhorizontal, stratigraphically upright lower limb. Deformation increases in intensity toward the hinge area of the fold, where primary sedimentary and volcanic fabrics are strongly overprinted by cleavage axial-planar with respect to upright to recumbent mesoscopic folds.

In the Arrastra Wash and lower Marcus Wash areas, metamorphism of the Winterhaven Formation is accompanied by remetamorphism of the Orocopia Schist, including reorientation of the regional fabric elements of the schist and development of a new metamorphic fabric with elements parallel to that in the Winterhaven Formation. This second fabric also is widespread in the granite of Marcus Wash. It is

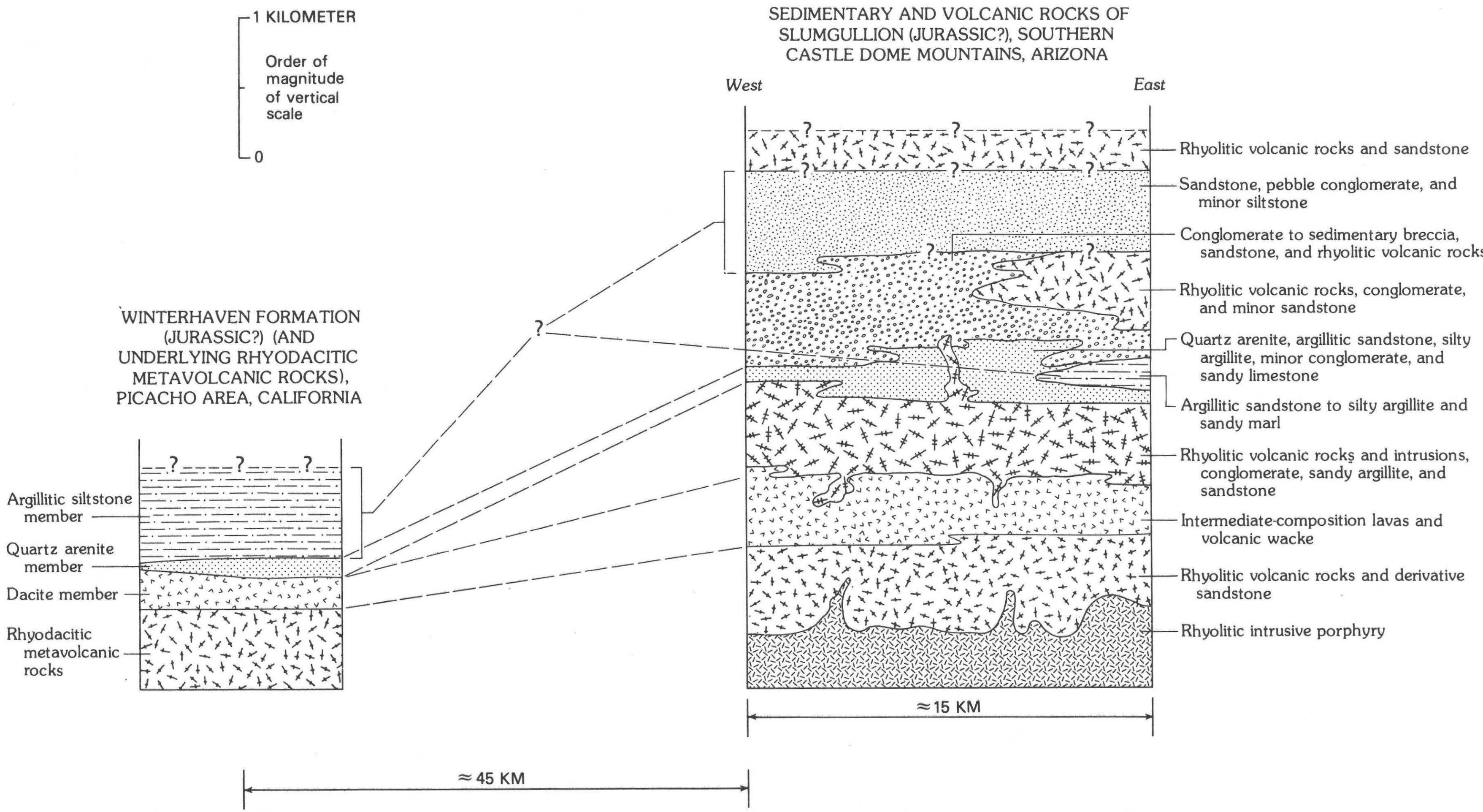


Figure 6. Generalized lithostratigraphic column for the sedimentary and volcanic rocks of Slumgullion and provisional correlations of the Slumgullion unit with the Winterhaven Formation. Arrangement of lithologic subunits within the column schematically represents observed and inferred facies relations within the Slumgullion unit across the 15-km width of the southern Castle Dome Mountains (fig. 1). Details of stratigraphic relations and thicknesses within these incipiently to moderately metamorphosed rocks are considerably more complex and uncertain than portrayed here, and stratigraphy of the upper part of the Slumgullion unit is highly uncertain, owing to intrusion by Jurassic granitoids, faulting, and Neogene volcanic cover. The dacite and quartz arenite members of the Winterhaven Formation and their counterparts within the Slumgullion unit are sufficiently distinctive, in lithology and sequence, that their correlation is straightforward. Correlation of the argillitic siltstone member of the Winterhaven Formation is less clear; it could correspond to either of two Slumgullion subunits.

unclear how much of the low-grade recrystallization of the Winterhaven Formation in the area from upper Marcus Wash westward to Indian Pass (fig. 2) and farther west (fig. 1) occurred during this metamorphic episode and how much occurred earlier, during intrusion of the Jurassic granodiorite (see next section) and (or) during movement on the Chocolate Mountains thrust.

BASAL CONTACT

In the Julian Wash and Arrastra Wash areas (fig. 2), the base of the Winterhaven Formation is a structurally concordant contact along which schistose rocks of the basal dacite member overlie schistose, rhyodacitic, quartz-phenocrystic metavolcanic rocks of presumed Jurassic age. This contact is neither obviously tectonic nor obviously depositional, but several lines of evidence favor the latter interpretation. In the Julian Wash area, rare sandstone interbeds within the dacite member of the Winterhaven Formation appear to have been derived from the underlying rhyodacitic volcanic rocks. In the Arrastra Wash area, the dacite member and the subjacent rhyodacitic metavolcanic rocks locally are interlayered and appear to be interbedded. Finally, in the Slumgullion unit of the southern Castle Dome Mountains, a lithologic unit that includes intermediate volcanic rocks similar to those of the basal member of the Winterhaven Formation clearly is interbedded with rhyodacitic volcanic to metavolcanic rocks (fig. 6). These relations, taken together, strongly suggest that the Winterhaven Formation stratigraphically overlies and interfingers with the rhyodacitic metavolcanic rocks.

These rhyodacitic metavolcanic rocks are intruded by the sphene-bearing hornblende-biotite granodiorite of Trigo Peaks in the southern Trigo Mountains (fig. 2). Both the rhyodacitic volcanic rocks and the granodiorite are considered Jurassic because of similarities in lithology and stratigraphic position to isotopically dated units elsewhere in the region of southern Arizona, southeastern California, and northern Sonora, Mexico (Dillon, 1976; Anderson and Silver, 1978; Crowl, 1979; Haxel and others, 1980, Powell, 1981; Hamilton, 1982; Wright and others, 1981; Tosdal, 1982; L.T. Silver, oral commun., 1983).

AGE

The Winterhaven Formation is older than earliest Tertiary K-Ar dates (Frost and Martin, 1983) and is lithologically dissimilar to any of the major Precambrian or Paleozoic tectonostratigraphic units of the southern Cordillera. Therefore, it is almost certainly of Mesozoic age. The field relations and regional lithologic correlations just described imply a Jurassic age. In the absence of direct paleontologic or isotopic age determinations, the age of the Winterhaven Formation is designated as Jurassic(?).

RELATIONS OF THE WINTERHAVEN FORMATION TO THE OROCOPIA SCHIST AND THE CHOCOLATE MOUNTAINS THRUST

The Orocopia Schist is the structurally lowest lithotectonic unit exposed in the region of the southeast corner of California and the southwest corner of Arizona (Haxel and Dillon, 1978). This schist forms the lower plate of the regionally extensive Chocolate Mountains thrust, the upper plate of which comprises almost all of the Mesozoic (and Proterozoic?) gneissic and granitoid rock units of the region. Elucidating the tectonic significance of the Winterhaven Formation with respect to the Orocopia Schist and the Chocolate Mountains thrust (Haxel, 1977; Crowell, 1981) involves choosing among four possibilities: (1) The Winterhaven Formation was originally a facies of the protolith of the Orocopia Schist, (2) the Winterhaven Formation was deposited nonconformably on the schist and upper-plate rocks, (3) the Winterhaven Formation and Orocopia Schist were originally juxtaposed along a fault younger than the Chocolate Mountains thrust, or (4) the Winterhaven Formation was originally part of the upper plate of the thrust. Evidence presented below indicates that the fourth possibility is the correct one.

Fault Contacts Between the Winterhaven Formation and the Orocopia Schist

Most present contacts between the Winterhaven Formation and the Orocopia Schist or gneiss of the upper plate of the Chocolate Mountains thrust are low- to high-angle faults. Most of these faults are largely or entirely of middle and (or) late Tertiary age because they cut the Oligocene and Miocene volcanic and sedimentary sequence or form part of some larger fault system that cuts that sequence. Evidence as to pre-middle Tertiary relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust is preserved in only a few places. This evidence indicates that the Winterhaven Formation is, or was, separated from the Orocopia Schist by two different late Mesozoic low-angle faults—the Chocolate Mountains thrust and a younger, low-angle normal fault.

In the Arrastra Wash area, the upper plate of the Chocolate Mountains thrust is the Jurassic granodiorite that intrudes the rhyolitic metavolcanic rocks which are inferred to stratigraphically underlie the Winterhaven Formation. Essentially continuous exposures of crystalline rocks, extending structurally upward from blastomylonitic granodioritic gneiss just above the Chocolate Mountains thrust to the basal dacite member of the Winterhaven Formation, are interrupted only by a couple of northwest-trending Tertiary (and Mesozoic?) faults (fig. 2). The vertical separation across these faults is probably appreciable, at least several kilometers, but the blastomylonitic gneiss northeast of the northeastern fault is clearly derived from the undeformed granodiorite to the southwest. These relations indicate that the

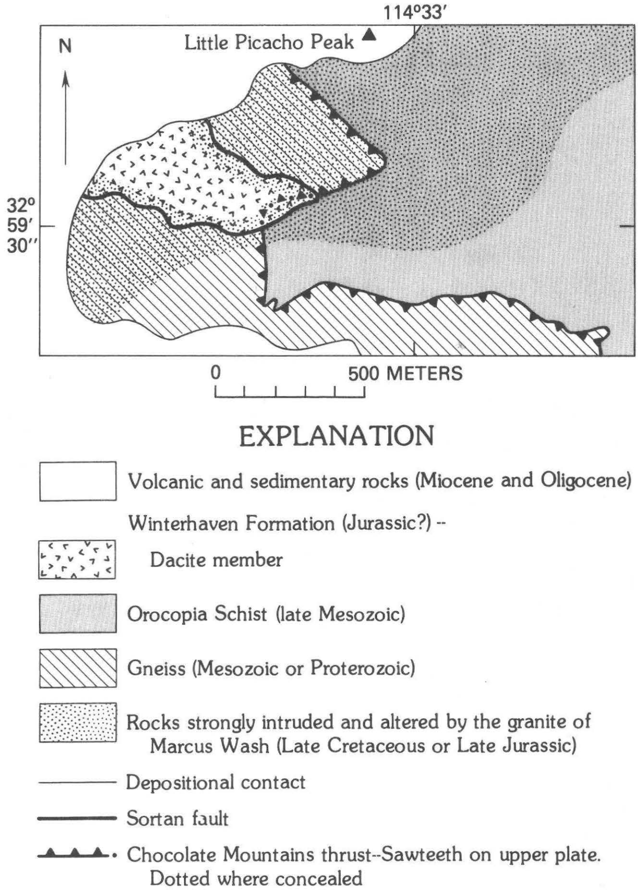


Figure 7. Relations between the Winterhaven Formation and the Orocopia Schist and Chocolate Mountains thrust in a small area southwest of Little Picacho Peak (see fig. 2 for location).

Winterhaven Formation was originally part of the upper plate of the Chocolate Mountains thrust.

The map pattern in the Arrastra Wash area (fig. 2) and the low metamorphic grade of the Winterhaven Formation compared to the Orocopia Schist and gneissic and granitic rocks of the base of the upper plate of the Chocolate Mountains thrust strongly suggest that the Winterhaven Formation originally was at a high structural level within the upper plate. This implies that where the Winterhaven Formation and the Orocopia Schist are in direct contact they must have been juxtaposed by faulting younger than the Chocolate Mountains thrust. In several areas east of the longitude of Picacho Peak (fig. 2), the contact between the Winterhaven Formation and both plates of the Chocolate Mountains thrust is, or was, a late Mesozoic low-angle normal fault younger than and distinct from the Chocolate Mountains thrust.

Evidence for the existence of this younger fault is found chiefly in three areas. In the first area, the antiform culmination between Little Picacho Wash and White Wash (fig. 2), the Winterhaven Formation entirely surrounds and largely faces outward from an antiform culmination consisting of Orocopia Schist and upper-plate gneiss separated by a short segment of the Chocolate Mountains thrust (fig. 3). The Winterhaven Formation, in turn, is surrounded by middle Tertiary sedimentary and volcanic rocks that dip outward on three sides from this crude dome. On the south side of the dome, the Winterhaven Formation and gneiss are separated by an intrusive tongue of the granite of Marcus Wash. Around most of the rest of the circumference of the dome the Winterhaven Formation is separated from the schist and gneiss by one of several faults that dip steeply to moderately outward toward the Winterhaven Formation. The overall geometry and tectonic setting of this fault system strongly argues against appreciable strike-slip movement. The north-dipping fault on the north side of the dome continues to the west, where it displaces middle Tertiary volcanic and sedimentary rocks downward against the Winterhaven Formation. The south-dipping fault along the southwest side of the dome is paralleled, 400 m to the south, by another south-dipping fault along which the middle Tertiary strata are faulted down against the Winterhaven Formation. The faults separating the Winterhaven Formation from the schist and gneiss are thus Tertiary dip-slip normal faults along which the Winterhaven Formation has been faulted downward against the schist and gneiss. This configuration suggests that, before Tertiary faulting, the Winterhaven Formation overlaid the schist and gneiss.

This conclusion is confirmed by relations in the second area, about 0.7 km southwest of Little Picacho Peak. Here, a small body of volcanic rocks of the basal dacite member of the Winterhaven Formation subhorizontally overlies upper-plate gneiss and, on its southeast side, Orocopia Schist and the Chocolate Mountains thrust (fig. 7). The rocks of this area are intimately intruded and strongly hydrothermally altered by the granite of Marcus Wash. In the few places where the actual contact between the volcanic rocks and schist or gneiss is exposed, either the two rock types are separated by a thin dike of granite, or the rocks straddling the contact are so severely altered that the contact can be located only to within a meter or so and its nature is unclear.

In the third area, along Sortan Wash, metamorphosed rocks of the Winterhaven Formation overlie the Orocopia Schist and a short segment of the Chocolate Mountains thrust along a low-dipping contact (fig. 8). Where locally relatively well exposed, this contact is marked by gouge and (or) microbreccia, and in several places it truncates the contact between the dacite and quartz arenite members of the Winterhaven Formation. This fault is here referred to as the Sortan fault.

The Sortan fault may be in part localized along the older Chocolate Mountains thrust (figs. 2, 8), in a manner analogous to localization of middle and late Tertiary normal faults along Mesozoic thrust faults (Haxel and Grubensky, 1984; Tosdal and Sherrod, 1985). In the area east of lower Marcus Wash and on the west side of Arrastra Wash (figs. 2, 8), the granite of Marcus Wash forms a small hemilaccolith intruded largely along the Sortan fault between the Winterhaven Formation and the Orocopia Schist (Haxel, 1977, app. 3).

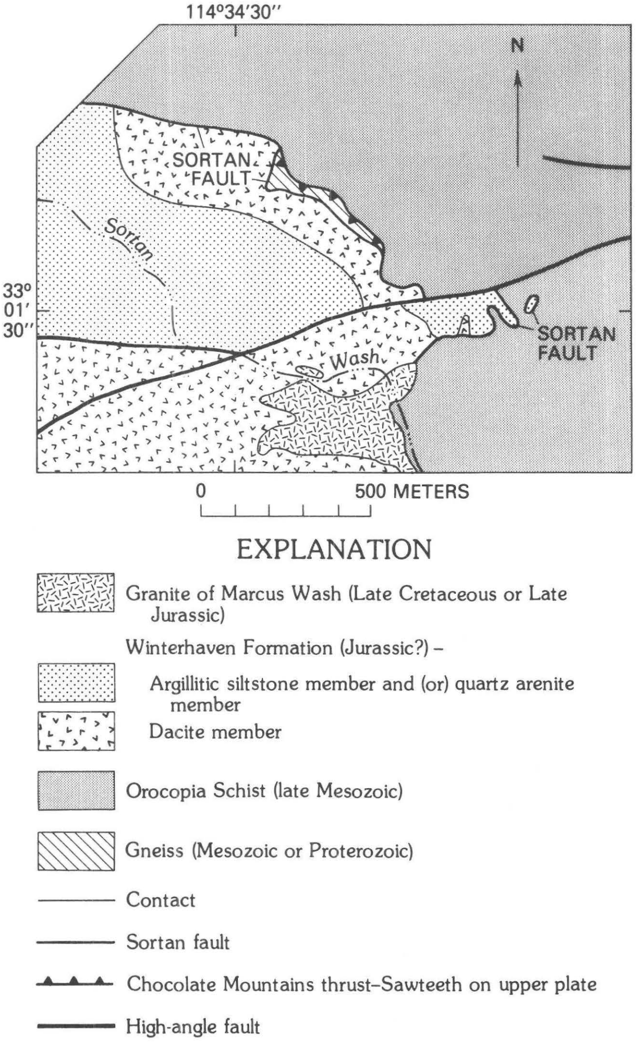


Figure 8. Relations among the Winterhaven Formation, the Orocopia Schist, and the granite of Marcus Wash in a small area along Sortan Wash (see fig. 2 for location).

The altered subhorizontal contact southwest of Little Picacho Peak (fig. 7) evidently is a segment of the Sortan fault, and the Sortan fault apparently also was the pre-middle Tertiary contact along which the Winterhaven Formation overlaid the Orocopia Schist and Chocolate Mountains thrust in the area west of Little Picacho Wash (fig. 3). Field relations in the three small areas where it is best preserved (figs. 3, 7, 8) unequivocally show that the Sortan fault postdates the Chocolate Mountains thrust and predates the granite of Marcus Wash; thus, this fault is of late Mesozoic age. The Sortan fault or fault system probably originally extended at least as far west as the Indian Pass area (fig. 2) and at least as far east as the southern Castle Dome Mountains (fig. 1). The Sortan fault appears to be a major structure in that a substantial thickness, probably about 5 to 10 km, of rocks of the upper plate of the Chocolate Mountains thrust evidently has been excised along the fault (fig. 9). The tectonic affinities of the Sortan fault are discussed below.

Distinction of the Winterhaven Formation from the Protolith of the Orocopia Schist

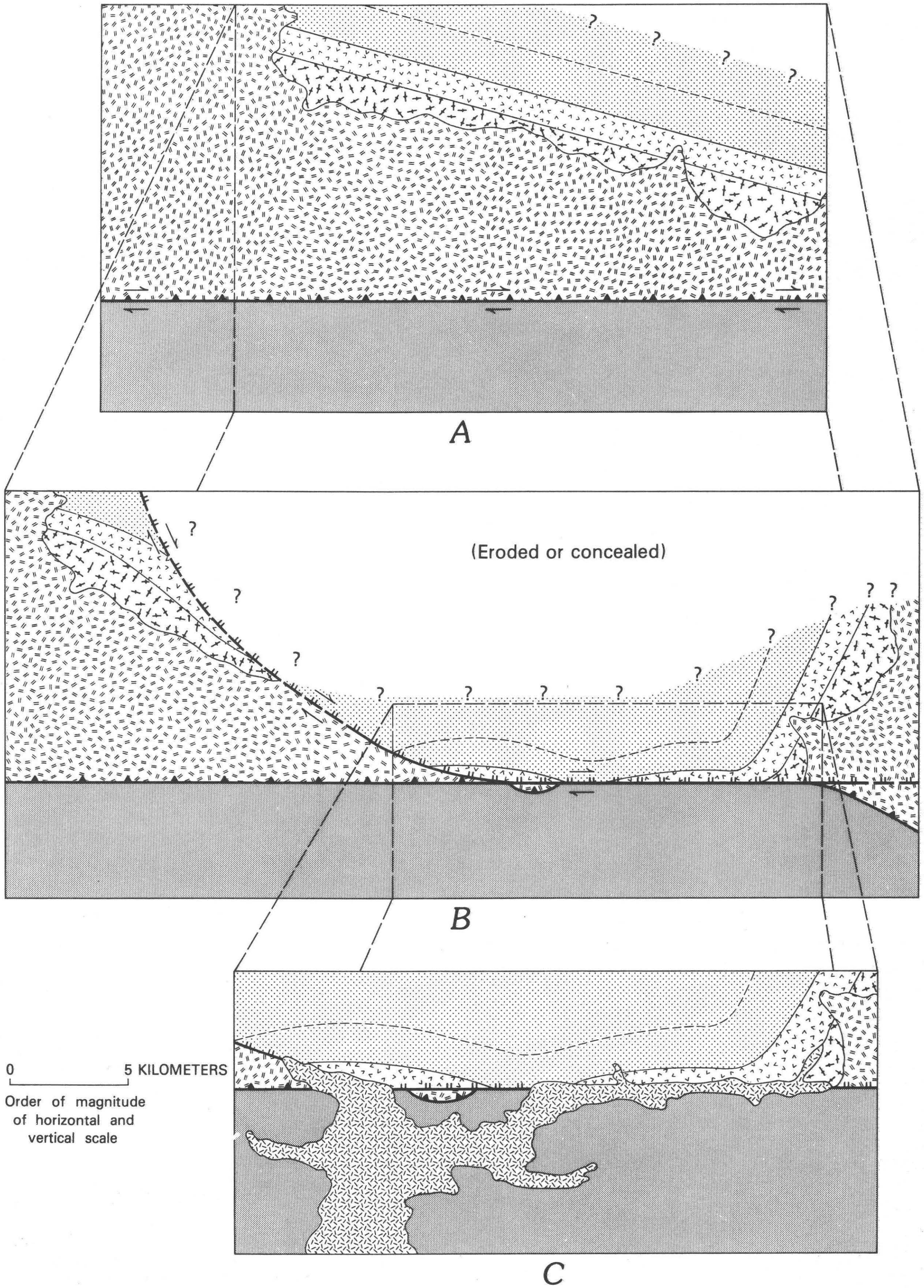
A suggestion in connection with the Winterhaven Formation is that it might represent a facies of the protolith of the Orocopia Schist. This possibility is not likely for several reasons. Although the Winterhaven Formation and the Orocopia protolith are both dominated by quartzofeldspathic to semipelitic sedimentary rocks of continental provenance, the two units have several significant lithologic, chemical, and tectonic contrasts indicative of deposition in distinct environments. The presence within the Orocopia protolith of basalt, ferromanganiferous chert, and peridotite indicates an oceanic or ensimatic environment; the Winterhaven Formation lacks mafic or ultramafic rocks, evidently rests on subaerial rhyolitic volcanic rocks (including welded tuff), and is inferred to represent an epicontinental environment. Quartz arenite and derivative quartzite in the Winterhaven Formation are detrital and lack the ferromanganiferous composition of the metachert of the Orocopia Schist. Psammitic and semipelitic rocks in the Orocopia Schist are commonly carbonaceous (graphitic), whereas those in the Winterhaven Formation are not. Metamorphosed dacitic and (or) andesitic volcanic rocks in the Winterhaven Formation of the Arrastra Wash-Marcus Wash area locally resemble some of the metabasite of the Orocopia Schist in outcrop but typically are finer grained, have a lower color index, and lack the albitic porphyroblasts that are rather common in Orocopia metabasite. Finally, the Winterhaven Formation and Orocopia Schist belong to the upper and lower plates, respectively, of the Chocolate Mountains thrust, which is part of a regionally extensive and presumably far-traveled thrust system in southern California and southwestern Arizona (Haxel and Dillon, 1978). Not only are the two formations separated by the thrust, but the oceanic protolith of the Orocopia Schist was deposited where it could subsequently be subducted or otherwise deeply tectonically buried, whereas the epicontinental Winterhaven Formation has evidently remained at relatively shallow crustal levels.

TECTONIC SIGNIFICANCE OF THE WINTERHAVEN FORMATION

As mentioned in the Introduction, the Winterhaven Formation is important for two reasons: because it is a part of the Mesozoic sedimentary record of the southeastern California-southwestern Arizona region and because of its relations to the Orocopia Schist.

Implications for the Age of the Orocopia Schist

Consideration of the significance of the Winterhaven Formation with respect to the Orocopia Schist requires some additional evidence from the central Transverse Ranges northeast of Los Angeles (fig. 1). This terrane was, before Neogene displacement along the San Andreas fault system


?
A
(Eroded or concealed)
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0
5 KILOMETERS
Order of magnitude
of horizontal and
vertical scale
C

EXPLANATION

- Granite of Marcus Wash (Late Cretaceous or Late Jurassic)
- Winterhaven Formation and underlying volcanic rocks and the sedimentary and volcanic rocks of Slumgullion, undivided (Jurassic?)–Divided into:
  - Sedimentary and volcanic rocks
  - Intermediate-composition volcanic rocks
  - Rhyodacitic volcanic and hypabyssal rocks
- Granitoid and gneissic rocks (Mesozoic and Proterozoic?)–Includes Jurassic granodiorite
- Orocopia Schist (late Mesozoic)
- Contact
- Trace of bedding
- Sortan fault (late Mesozoic)–Ticks on upper plate. Dashed where approximately located; queried where uncertain. Arrows indicate direction of relative movement
- Chocolate Mountains thrust (late Mesozoic)–Sawteeth on upper plate. Arrows indicate direction of relative movement

Figure 9. Schematic tectonic diagrams showing how strata of the Winterhaven Formation and the sedimentary and volcanic rocks of Slumgullion, originally part of the upper plate of the Chocolate Mountains thrust (A), were displaced downward onto the Orocopia Schist (lower plate of the thrust) by movement on the Sortan fault (B). Development of the Sortan fault was followed by intrusion of the granite of Marcus Wash (C). Figure 9B represents upper-crustal extension of area of figure 9A; figure 9C is an enlargement of part of figure 9B. The Chocolate Mountains thrust and the Sortan fault are both late Mesozoic—younger than 163 m.y. and older than the pre-earliest Tertiary (pre-60 m.y.) granite of Marcus Wash. Granitoid and gneissic rocks of the upper plate of the Chocolate Mountains thrust include the Jurassic granodiorite that intrudes the Slumgullion unit and the volcanic rocks underlying the Winterhaven Formation. These diagrams are not cross sections through any single area of the crust but, instead, are composite sketches, not to scale, based largely on map patterns in the area from the Gavilan Hills eastward to Sortan Wash and northward to upper Arrastra Wash (figs. 2, 8), and in the southern Castle Dome Mountains (fig. 1).

(Crowell, 1979), adjacent to the southern Chocolate Mountains (Dillon, 1976; Ehlig, 1981; Powell,1981; Silver, 1982). The Pelona Schist and the synmetamorphic Vincent thrust of the central Transverse Ranges are considered tectonically equivalent to the Orocopia Schist and Chocolate Mountains thrust of southeastern California. (The Rand Schist of the northern Mojave Desert, though similar to the Orocopia and Pelona Schists, is not discussed here because it apparently was never contiguous with them, at least at presently exposed crustal levels.)

The role of the Orocopia and Pelona Schists in the tectonic evolution of the southern Cordillera remains uncertain (Haxel and Dillon, 1978; Burchfiel and Davis, 1981; Crowell, 1981; Ehlig, 1981; Jacobson, 1983a; Silver, 1983; Vedder and others, 1983). Because of the rapid tempo of events during Late Cretaceous and early Tertiary time (Dickinson, 1981), the age of the Orocopia Schist needs to be determined as precisely as possible. The relations described above between the Orocopia Schist and Winterhaven Formation are important in this regard.

The Orocopia and Pelona Schists were pervasively metamorphosed under high-pressure upper greenschist- to lower amphibolite-facies conditions and have undergone multiple penetrative folding and transposition (Graham and England, 1976; Haxel and Dillon, 1978; Jacobson, 1983a, b). In contrast, much of the Winterhaven Formation is only incipiently or partially recrystallized, probably in the lower greenschist facies, and has not been penetratively deformed. (Where locally more strongly recrystallized and deformed, the Winterhaven Formation was affected by a separate and younger metamorphic and magmatic event that also remetamorphosed the Orocopia Schist.) The Winterhaven Formation clearly has not been subjected to the deformational and metamorphic event that produced the Orocopia Schist. The Orocopia Schist was metamorphosed at considerable depth beneath the upper plate of the synmetamorphic Chocolate Mountains thrust (Dillon, 1976; Haxel, 1977; Ehlig, 1981; Jacobson, 1983c). The Winterhaven Formation, originally part of the upper plate of the thrust, has not been subject to this deep tectonic burial, and it overlies both plates of the thrust along the pre-60-m.y. (Frost and Martin, 1983), shallow-level Sortan fault. Therefore, the Orocopia Schist was returned to upper-crustal levels, and the overlying Chocolate Mountains thrust breached, before 60 m.y. ago.

This conclusion implies that metamorphism of the Orocopia and Pelona Schists was somewhat earlier than previously thought. The currently accepted metamorphic age of these schists is based largely on Rb-Sr mineral-isochron and K-Ar whole-rock minimum ages of 52-59 m.y. from the Pelona Schist and the Vincent thrust zone (Ehlig, 1981). A sequence of several major events—return of the Orocopia Schist to the upper crust, juxtaposition against the Winterhaven Formation, remetamorphism, and intrusion by the granite of Marcus Wash—intervened between the metamorphism of the Orocopia Schist and setting of K-Ar dates about 60 m.y. ago. Thus, the 52- to 59-m.y. isotopic dates for the Pelona Schist and Vincent thrust are postmetamorphic cooling ages. The primary metamorphic age of the Orocopia and Pelona Schists must be appreciably older than 60 m.y. and is almost certainly pre-Tertiary.

The 80±10-m.y. U-Pb zircon age (Carter and Silver, 1972) of a granodiorite apparently in the upper plate of the Vincent thrust has been considered a maximum age for the Vincent thrust and metamorphism of the Pelona Schist (Ehlig, 1981).

However, three factors indicate that this isotopic age may not provide a straightforward maximum age for the thrust and schist. First, the dated granodiorite lithology cannot be unequivocally tracked into the Vincent thrust zone (L.T. Silver, oral commun., 1983; P.L. Ehlig, oral commun., 1984). Second, the Chocolate Mountains thrust has been modified or replaced by both the late Mesozoic low-angle Sortan fault and numerous middle and late Tertiary low-angle faults, and Tertiary low-angle faults in the southern Arizona-southeastern California region are not uncommonly localized along Mesozoic thrust faults (Frost and others, 1982; Haxel and Grubensky, 1984; Tosdal and Sherrod, 1985). Third, observations presented by Evans (1982) suggest that some segments of the Vincent thrust may have been reactivated during faulting younger than the original formation of the fault zone and metamorphism of the Pelona Schist. The second and third of these factors suggest that the 80-m.y.-old granodiorite in the central Transverse Ranges may be cut not by the Vincent thrust but by younger fault(s).

The principal data bearing on the metamorphic age of the Orocopia and Pelona Schists can be summarized as follows. A concordant U-Pb age of 163 m.y. on zircon from a metamorphosed dioritic dike in the Orocopia Schist (Mukasa and others, 1984) provides a maximum age. As explained above, metamorphism must be appreciably earlier than 60 m.y. (K-Ar dates of Frost and Martin, 1983). Field relations and isotopic ages in the central Transverse Ranges (Carter and Silver, 1972; Ehlig, 1981; D.J. May, oral commun., 1985) suggest, but do not prove, that the metamorphism is Late Cretaceous or earlier. The probable age of metamorphism of the Orocopia and Pelona Schists is thus Late, but not latest, Cretaceous; an early Tertiary age is unlikely, and a Late Jurassic age cannot be precluded.

Tectonic Affinities of the Sortan Fault

A puzzling aspect of the low-dipping late Mesozoic Sortan fault is its normal-fault geometry—it places the Winterhaven Formation, originally part of the upper plate of the Chocolate Mountains thrust, over the Orocopia Schist, the lower plate of the thrust (figs. 3, 7-9). Pre-Tertiary low-angle normal faults have not been widely reported in the southern Cordillera, the late Mesozoic tectonic evolution of which was generally characterized by thrust faulting and crustal shortening rather than normal faulting and crustal extension. It is unclear whether the Sortan fault represents local extension within the overall framework of late Mesozoic shortening or a widespread but previously unrecognized late Mesozoic extensional episode.

Field relations in the Sortan Wash-Arrastra Wash area (figs. 2, 8, 9c) suggest that movement on the Sortan fault was part of the same event as metamorphism of the Winterhaven Formation and emplacement of the granite of Marcus Wash. If so, this composite event may be related to the Late Cretaceous and early Tertiary episode of thrust faulting, regional metamorphism, and granitic plutonism that affected the region from southeastern Arizona to southeastern California (Keith and others, 1980; Reynolds, 1980; Hamilton, 1982; Miller and others, 1982; Haxel and others, 1984; Tosdal, 1984b). Within this crustal-shortening regime, localized extension might have occurred by either of two mechanisms. First, extensional faults might have formed as a result of gravitational relaxation along a topographic front within the thrust belt (Royden and Burchfiel, 1985). Second, extension could have taken place within the upper plate of a downward-steepening, thick-skinned thrust fault (Coward, 1983), in particular the Mule Mountains thrust; the Sortan fault might thus be akin to a keystone fault (Wise, 1963).

Two considerations, in addition to the existence of the Sortan fault, indicate that late Mesozoic low-angle normal faults could be more common than previously suspected. (1) Evidence presented by Silver and others (1984) and C.E. Postlethwaite and C.E. Jacobson (written commun., 1985) suggests that one of the faults overlying the Rand Schist (which is similar to the Orocopia Schist) is not the thrust fault beneath which the schist was originally metamorphosed but, instead, a late Mesozoic or early Tertiary low-angle normal(?) fault comparable to the Sortan fault. (2) Coney and Harms (1984) hypothesized that Tertiary crustal extension in the Cordillera was caused by lateral spreading consequent to Mesozoic crustal thickening, and that extension was initiated or facilitated by the thermal input accompanying Tertiary magmatism. This model suggests that the Tertiary extensional episode was not necessarily unique. Late Mesozoic crustal extension may have occurred, boundary conditions permitting, in regions where earlier Mesozoic crustal thickening was followed by a separate, late Mesozoic thermal episode. In this context, crustal thickening caused by emplacement of the upper plate of the Chocolate Mountains thrust may have been followed by extensional deformation, including development of the Sortan fault, at the time of the thermal episode in which the granite of Marcus Wash was emplaced and the Winterhaven Formation metamorphosed.

If there was a widespread episode of late Mesozoic crustal extension, some or much of the postmetamorphic uplift of the tectonically buried Orocopia and Pelona Schists may have taken place during that episode (C.E. Postlethwaite and C.E. Jacobson, written commun., 1985). In southeastern California, the original tectonic stratigraphy that characterizes the Chocolate Mountains thrust zone at the top of and overlying the Orocopia Schist is widely preserved (figs. 1, 2; Dillon, 1976; Haxel, 1977); only locally has the thrust been disrupted by the Sortan fault. This observation has two important implications. First, the Chocolate Mountains thrust and part of its crystalline upper plate were uplifted along with the Orocopia Schist. Second, because the Chocolate Mountains thrust is extant over a wide area, the Sortan fault is not simply a wholesale reactivation of the thrust but, instead, a new and independent structure.

Possible Correlation with the McCoy Mountains Formation

The McCoy Mountains Formation is a Jurassic and (or) Cretaceous siliciclastic sedimentary and metasedimentary sequence, as much as 7 km thick, exposed in the region around Blythe, Calif., and Quartzsite, Ariz. (fig. 1; Pelka, 1973; Harding and Coney, 1985). This formation is definitely older than latest Cretaceous K-Ar minimum ages of crosscutting plutons, faults, and veins (Pelka, 1973; Reynolds, 1980; Tosdal, 1984a; L.B.G. Pickthorn, oral commun., 1985), but other data as to the age of the formation are equivocal or seemingly contradictory. The basal strata of the McCoy Mountains Formation are apparently interbedded with volcanic rocks of probable Early and (or) Middle Jurassic age (Harding, 1982), and paleomagnetic data suggest that the formation, or at least its lower part, is older than middle Late Jurassic (Harding and others, 1983). However, the upper part of the formation contains fossil angiosperm wood of probable mid-Cretaceous or younger age. These data, if all taken at face value, imply that either the McCoy Mountains Formation spans a considerable part of Jurassic and Cretaceous time or, more likely, the formation consists of two distinct sedimentary units, one Early and (or) Middle Jurassic and the other middle and (or) later Cretaceous, separated by an unrecognized unconformity (compare with Miller, 1966).

The southern boundary of the known extent of the McCoy Mountains Formation is the south-dipping late Mesozoic Mule Mountains thrust (Tosdal, 1982), the upper plate of which is composed largely of Jurassic granodiorite. This granodiorite extends southward to the lithologically identical granodiorite of Trigo Peaks that intrudes the metavolcanic rocks beneath the Winterhaven Formation (fig. 2). The presence of several distinctive lithologic units cut by (and thus older than) the Mule Mountains thrust in both plates of the thrust indicates that displacement on the thrust is relatively small, probably about 1-10 km (Tosdal, 1984a, b).

The Winterhaven Formation and the lower part of the McCoy Mountains Formation are both of probable Jurassic age, have a broad lithologic similarity, are exposed within about 70 km of one another, and are separated by a fault of minimal displacement. These considerations suggest that the two units could be correlative and related.

The Winterhaven Formation and the lower part of the McCoy Mountains Formation have two significant stratigraphic similarities. First, both formations evidently rest depositionally on and, at least locally, interfinger with Jurassic silicic volcanic rocks. Second, the quartz arenite member and the argillitic siltstone member of the Winterhaven Formation appear to correspond to the basal sandstone members and the mudstone member, respectively, of the McCoy Mountains Formation (stratigraphic nomenclature of Harding and Coney, 1985). In particular, the quartz arenite member of the Winterhaven Formation, the probably correlative unit within the sedimentary and volcanic rocks of Slumgullion (fig. 6), and basal sandstone member 1 of the McCoy Mountains Formation in the area southeast of Quartzsite all consist of or include a lithologic association of interbedded light-tan or gray quartz arenite, dark-purplish or maroonish-gray siltstone or mudstone, and minor quartzite-pebble conglomerate and brown-weathering arenaceous limestone. This distinctive lithologic association suggests that the Winterhaven Formation, the Slumgullion unit, and the lower part of the McCoy Mountains Formation may all record the same depositional episode or sedimentary environment. Despite the general similarity of the silicic volcanic (and related hypabyssal) rocks beneath the Winterhaven and McCoy Mountains Formations, the dacite member of the Winterhaven Formation has no counterpart in the McCoy Mountains Formation. If correlation of the Winterhaven Formation with the lower part of the McCoy Mountains Formation is valid, then the dacite member is more limited in extent than the underlying silicic volcanic rocks and overlying sedimentary rocks, and probably was deposited over a smaller area. This restricted distribution may, in part, reflect the lesser mobility of intermediate volcanic flows compared to silicic ash-flow tuff. In summary, correlation of the Winterhaven Formation and the lower part of the McCoy Mountains Formation is reasonable, even likely, but cannot be proven or disproven until additional geochronologic data are available.

The Mule Mountains thrust has been interpreted as a tectonostratigraphic terrane boundary separating the McCoy Mountains Formation, which has a North American provenance, from suspect terranes to the southwest (Harding and Coney, 1985). This interpretation is based largely on the apparent absence in the region southwest of the McCoy Mountains Formation of Proterozoic and Paleozoic rocks of cratonic North American affinities. However, the several similarities between the McCoy Mountains and Winterhaven Formations and their underlying volcanic and hypabyssal rocks, in addition to the evidence for minimal slip along the Mule Mountains thrust, indicate caution in inferring a major late Mesozoic tectonostratigraphic terrane boundary between the McCoy Mountains Formation and the Winterhaven Formation. Although these stratigraphic and structural ties are geometrically imprecise and do not necessarily preclude some displacement of the Winterhaven Formation along and (or) perpendicular to the continental margin, they do suggest that the Winterhaven Formation is indigenous to southwestern North America. If future research shows that the Winterhaven Formation (and the sedimentary and volcanic rocks of Slumgullion) are, indeed, related to the McCoy Mountains Formation, then any late Mesozoic or Tertiary suture between indigenous and suspect or exotic tectonostratigraphic terranes must lie either within the upper plate of the Chocolate Mountains thrust south of the outcrop area of the Winterhaven Formation or structurally below the upper plate of the Chocolate Mountains thrust.

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