OROCOPIA MOUNTAINS DETACHMENT SYSTEM: PROGRESSIVE DEVELOPMENT OF A TILTED CRUSTAL SLAB AND HALF-GRABEN SEDIMENTARY BASIN DURING REGIONAL EXTENSION

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Abstract

Gneissic and granitic rocks sit structurally above the Mesozoic Orocopia Schist in the Orocopia and Chocolate Mountains of southeastern California (fig. 1). The gneissic and granitic units were originally emplaced above the schist along a Late Mesozoic thrust as is generally believed. In the Orocopias, the east-dipping system of faults that currently juxtapose the units, however, is a major system of anastamosing normal faults, which records a continuum of deformation from ductile mylonitic textures to brittle fault gouge. The middle to upper-crustal deformation by large-scale extension is a continuation of the highly extended terrane along the Colorado River and that to the west in the California Continental Borderlands. This crustal extension in the Orocopia-Chocolate Mountains region helped localize the San Andreas fault system and is itself offset along the San Andreas to numerous exposures west of the main strand of the San Andreas, including many oil-bearing basins.

This continuum of mylonitic to brittle fault fabrics of the Orocopia extensional system is superimposed on the earlier (Late Cretaceous) schist-forming metamorphism and deformation. Transport within the extensional system is to the east, rather than the regional NE-SW movement direction, suggesting perhaps 45 degrees of clockwise rotation or oroclinal bending during either the development of the detachment system or its deformation by later transform movement. The range itself represents a tilted crustal slab that developed during Tertiary extension, exposing the Mesozoic Orocopia Schist and related deformational features. The antiformal character of the schist package appears to be a large-scale flexure, or "drag," that is overprinted by the kinematically related Tertiary normal faults. Eocene mylonites in the ductile portion of the fault zone are synchronous with the deposition of the marine Maniobra Formation at the base of the Diligencia basin. Miocene normal faults offset the syntectonic Miocene Diligencia Formation with a complex series of dominos and folds over underlying crystalline tilt blocks. The Orocopias are thought to have been

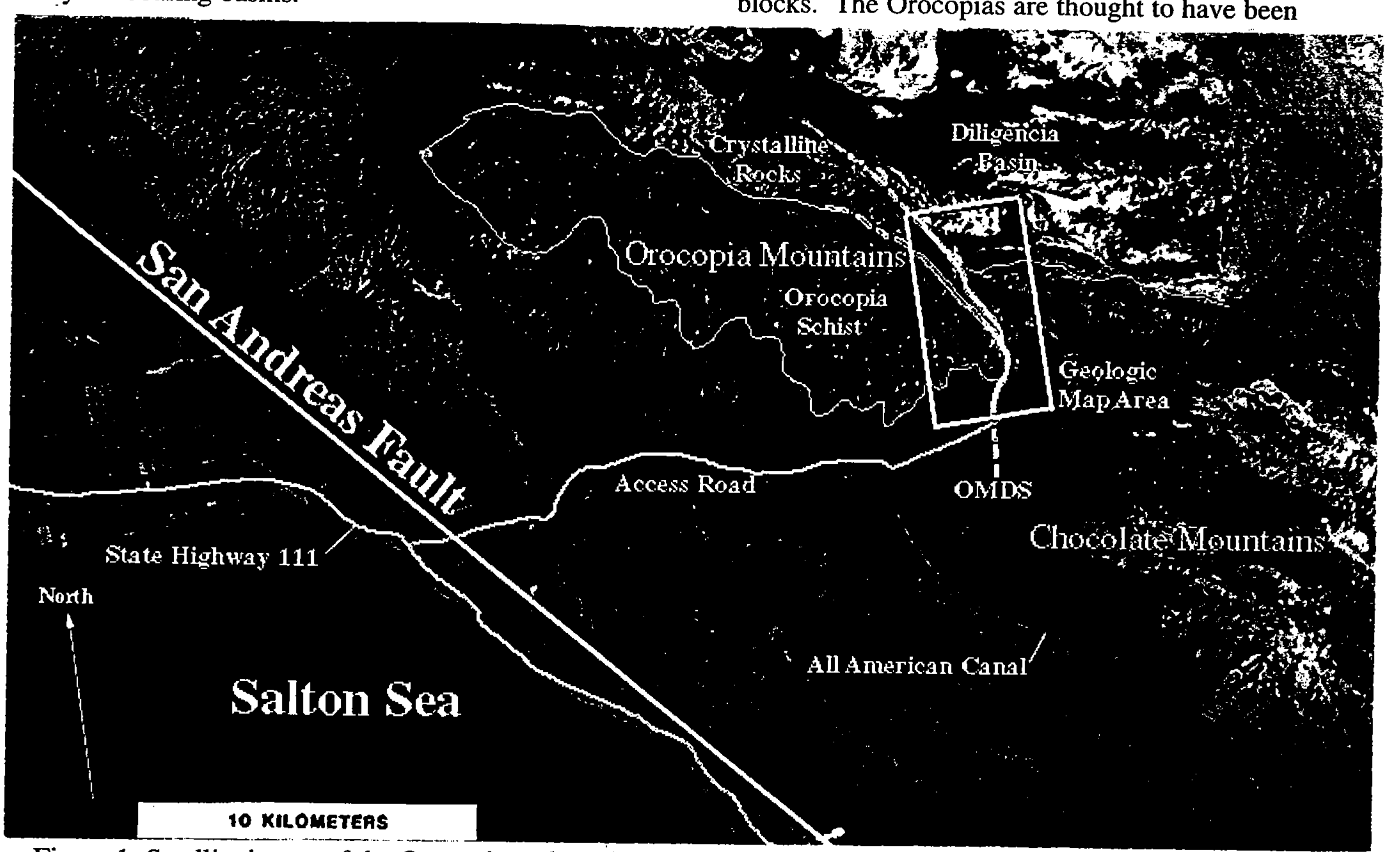

Figure 1. Satellite image of the Orocopia and northern Chocolate Mountains region, showing the Salton Sea, the San Andreas Fault, the Orocopia Schist, the Orocopia Mountains Detachment System, the Diligencia Basin, the Salton Creek drainage, State Highway 111, the access road, the All American Canal and the geologic map area (fig 2).

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underlain by subhorizontal ductile middle crust at the time of extension as is imaged seismically to the south in the Chocolate Mountains area, with tilting of upper-crustal crystalline and sedimentary rocks occurring above this zone of ductile motion.

The moderately to gently inclined Miocene normal faults developed a thick chlorite breccia zone, numerous fault ramps, and a thick Miocene continental section, the Diligencia Formation. The sedimentary section in the Diligencia basin is a tape recording of the Tertiary extension during its development, as well as a tape recording of the superimposed strike-slip system that deformed the basin and the extensional faults. The detachment system is offset along the San Andreas to the margins of the oil-bearing Soledad and Cuyama basins on the west side of the fault. The timing and style of deformation in the Orocopias is similar to that in the California borderlands and southern Los Angeles basin. Tilting of the large-scale crustal blocks not only exposed once middle-crustal rocks adjacent to sedimentary basins, but likely helped to localize later strike-slip faulting.

Location

The Orocopia Mountains are located northeast of the Salton Sea and the San Andreas fault just northwest of the Chocolate Mountains in Riverside County, California. Access into the heart of the range is best achieved along good dirt roads along the south side of the range. To enter the Orocopias from these roads, take State Highway 111 to the cross street at the Salton Sea State Campground and turn east toward the mountains, following the signs to the All American Canal frontage road. Follow Canal Road southeast until it intersects Bradshaw Road at pump station 24, then turn up the alluvial fan along straight Bradshaw Road. Bradshaw Road traverses alluvial fan deposits derived from the Orocopias and parallels the E-W trending Salton Creek Wash separating the Orocopias from the Chocolate Mountains. Approximately 1.5 miles after turning onto Bradshaw Road, a north-trending good dirt road provides access up the major wash that drains the most geologically important area in the range (fig. 2).

Background

The pioneering work of Tom Dibblee (1954) and John Crowell (1957) led to a description of the variety of rock types and structural relations exposed in the Orocopia Mountains (Crowell, 1962; Crowell and Walker, 1962). These studies provided an estimation of minimum offset along the San Andreas Fault from the exposures of very similar rocks present in the San Gabriel Mountains (Ehlig, 1958)

At the time of these investigations, deformation in the Cordillera was thought to be mostly Mesozoic. The juxtaposition of granite and gneiss over schist in the Orocopias was therefore interpreted as a Mesozoic thrust (Ehlig, 1968; Crowell, 1974). Crowell (1975) proposed that the deformation in the Orocopias was due to Late Cretaceous deep-seated faulting, forming mylonite and blastomylonite, and followed by shallow reactivation. Crowell's mapping and description of the deformation was essentially correct and provides the basis for all subsequent studies.

Regional Relationships

The Orocopia Schist is part of a regional package of metasedimentary rocks also referred to as the Pelona, Orocopia, Rand and Portal Ridge (POR) schists. The POR schists are isolated bodies of a pervasively metamorphosed and deformed graywacke with subordinate basalt, ferromanganiferous chert, siliceous limestone and ultramafic rock in southern California and southwestern Arizona (Haxel and Dillon, 1978; Haxel and others, 1988). The POR schists underlie faults that are collectively termed the Vincent-Chocolate Mountains (VCM) thrust by Haxel and Dillon (1978). The Orocopia Schist is similar in many ways to the Catalina Schist, although the former has undergone a more protracted history of metamorphism and deformation (Jacobson and Sorensen, 1986).

Interpretations

The schist is generally believed to be a package of Triassic-Jurassic, continental margin, oceanic sedimentary and volcanic rocks that were regionally metamorphosed in Late Cretaceous time due to overthrusting of a continental block of Precambrian and Mesozoic crystalline rocks (Haxel and Dillon, 1978; Ehlig, 1981; Mukasa and others, 1984; Haxel and Tosdal, 1986; Jacobson and others, 1988). The direction of Late Cretaceous thrusting is of some debate based on exposures of faults at the top of the schist and their identification as the VCM thrust. All contacts of the POR schist with overlying rocks are not the Mesozoic thrust system, however. Some of these contacts appear to be Tertiary normal faults that have offset the schist and its Mesozoic contact with the overlying crystalline units.

Significant deformation along the zone traditionally interpreted as the Vincent-Orocopia-Chocolate Mountains thrust has been produced by crustal extension and exhumation of the schist from middle to deep crustal depths in early Tertiary time (Frost and others, 1982; Frost and Martin, 1983a, 1983b; Silver and others, 1984; Drobeck and others, 1986; Silver and Nourse, 1986; Postlethwaite and Jacobson, 1987; Jacobson and others, 1988, 1990;

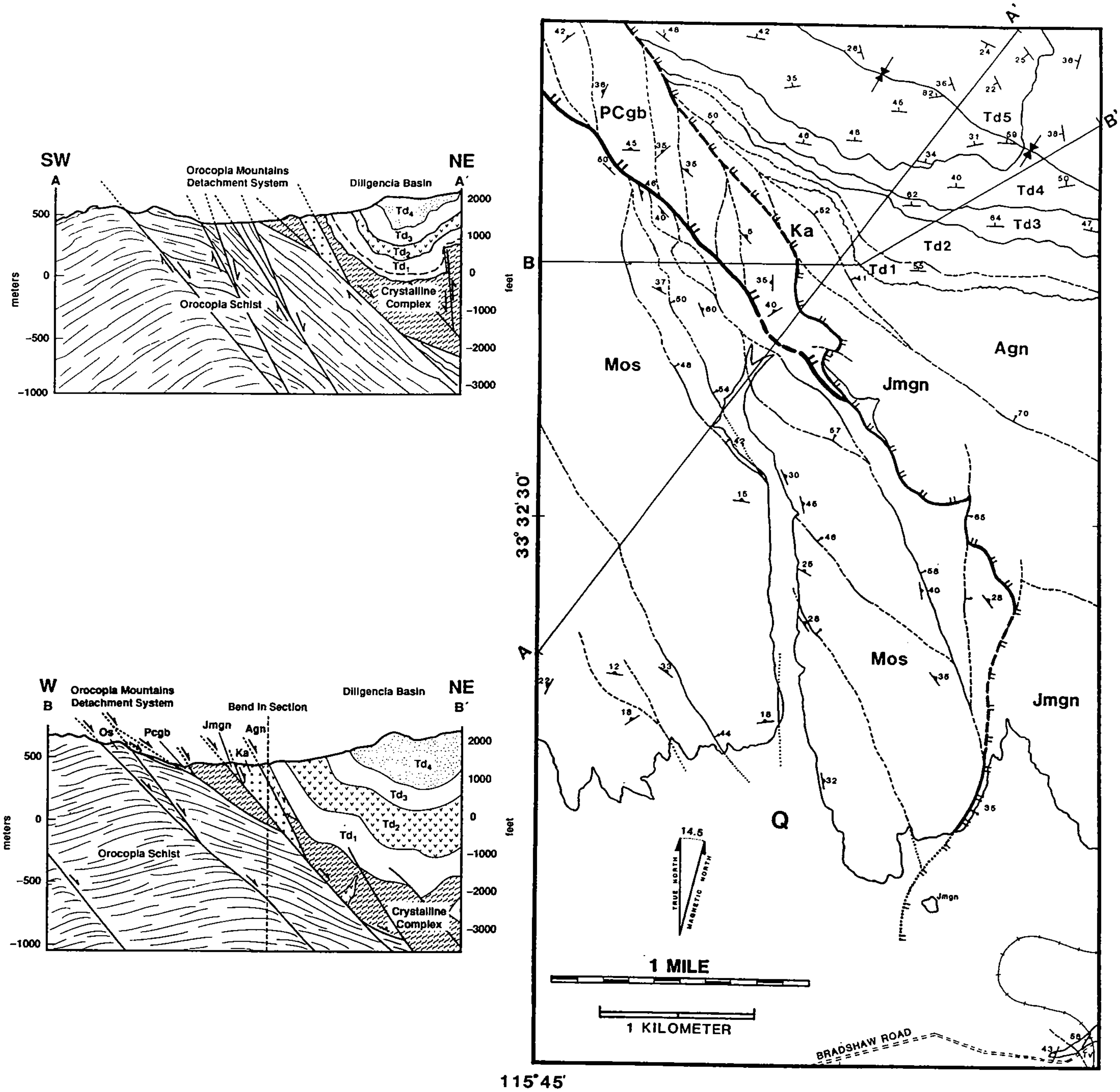

Figure 2. A geologic map of a portion of the Orocopia Mountains. The thick line represents the contact between upper and lower plate along the Eocene mylonitic boundary called the Orocopia Mountains Detachment Fault (**OMDF**), double ticks are on the hanging wall. The thinner double ticked line is the Diligencia Detachment Fault (**DDF**) which is shown to truncate OMDF in the central portion of the map. Map units are designated: Lower plate; **Mos**, is the Mesozoic Orocopia Schist. Upper plate; **PCgb**, is a blue quartz banded gneiss of possible Precambrian age; **Jmgn**, is a suite of mafic gneiss including diorite, gabbro and anorthosite; **Agn**, is an alkalai feldspar augen gneiss; **Ka**, is a tabular unit of adamelite. Diligencia basin sedimentary rocks; **Td1** through **Td5** are part of the early Miocene Diligencia Formation with **Td3** being the 20-23 Ma basalt; Tv represents volcanic rocks in the southeastern map area that are tilted back into DDF as it trends south out of the range. **Q**, is Quaternary alluvium. Figure 2A is a cross section from A-A' and Figure 2B is a cross section from B-B' across the Orocopia Mountains Detachment System.

Haxel and others, 1988). In the Orocopia Mountains, the contact between the schist and structurally overlying crystalline rocks has been historically termed the "Orocopia Thrust" (Crowell, 1974).

The important question to address is whether the presently exposed kinematic indicators along the fault were produced during prograde metamorphism of the schist related to the emplacement of the continental fragment along a thrust, or whether they are the shear zone features resulting from exhumation of the schist from the middle crust during extension. In the Orocopias, there appear to be two episodes of Tertiary extension that are superimposed on the earlier phases of Mesozoic shortening. Isotopic studies have indicated largely Eocene K-Ar cooling ages for the schist in the San Gabriel Mountains (Miller and Morton, 1977, 1980). In the Orocopia Mountains, Jacobson (1990) provides Ar-Ar evidence for Eocene mylonitization. Further isotopic data obtained from this study indicate that cataclastic deformation in the Orocopias ranges from latest Oligocene through mid-Miocene.

Seismic profiling in southeastern California has shown that ranges are deformed as tilted crustal blocks forming sedimentary basins in half grabens bounded by detachment faults (Pridmore and Craig, 1982; Morris and others, 1986a; 1986b: Frost and Okaya, 1986; Frost and others, 1987; Duke, 1991; Frost and Heidrick, 1996) The Tertiary tilting of these upper-crustal blocks and their basins must be considered when describing the present orientations of Mesozoic and Tertiary rock fabrics. The Orocopias appear to be an excellent example of one of these tilted crustal slabs exposing the once middle-crustal Orocopia Schist along the footwall of the Orocopia Mountains detachment system (Robinson and Frost, 1989). Microstructural evidence providing kinematic sense of movement across the shear zone historically termed the "Orocopia Thrust" indicates that the zone is a normal fault (Robinson and Frost, 1989). Isotopic and structural data both indicate that the "Orocopia Thrust" is better viewed as a ductile normal fault and an early-formed structure in the Orocopia Mountains Detachment System (Robinson and Frost, 1989).

Orocopia Mountains Detachment System

Work in the Orocopia Mountains has revealed kinematic data that agree with a northeast direction of transport for the upper plate (Simpson, 1986; Robinson and Frost, 1989). Mylonitization and retrograde metamorphism of the schist are the result of a continuum of extensional deformation that progressed from ductile to brittle conditions. Though the rock masses in the Orocopias were originally juxtaposed by thrusting, probably related to Late Cretaceous plate convergence, geochronologic data show that mylonitization along the "Orocopia Thrust" is Eocene in age (Jacobson , 1990). Mylonitic deformation was the result of initial exhumation of the Orocopia Schist from the middle crust which was synchronous with primary basin development and marine deposition of the Eocene Maniobra Formation (Crowell and Susuki, 1959). The present contact between upper and lower plate, once called the "Orocopia Thrust" (Crowell, 1974), is a normal fault that we propose naming the Orocopia Mountains Detachment Fault, OMDF. This ductile mylonitic feature formed during initial exhumation of the Orocopia Schist which was coeval with the deposition of Eocene marine strata. This normal fault appears to offset whatever the original upper contact of the Orocopia Schist was ("Orocopia Thrust"), so that the nature of this contact is not observable in the Orocopia Mountains. This original contact is present on the southwest side of the Chocolate Mountains tilted crustal slab to the south and appears to be both deformational and intrusive in character.

Continued uplift of the lower-plate Orocopia Schist was accommodated by brittle deformation along the Clemens Well and other, sub-parallel faults as the extensional fault system progressed through upper-crustal levels (Goodmacher and others, 1989; Robinson and Frost, 1989). The Clemens Well fault is a northwest-oriented structure that has been generally attributed to strike-slip deformation (Powell, 1981, 1993). We interpret the Clemens Well fault to be one of a series of anastamosing upper-plate normal faults, although it may well have accommodated some strike-slip motion as well. These faults appear to record the brittle overprint of faulting on the mylonitic textures preserved along the earliest-formed segments of the extensional fault system.

Microbreccia that truncates the ductile OMDF has been dated at 25 Ma (M. Shafiqullah, written commun., 1991). We propose the name Diligencia Detachment fault, DDF, for the basal microbreccia ledge that is clearly seen cutting mylonite of the OMDF. Faults with geometries like the Clemens Well appear to be part of this brittle deformation that forms a prominent brittle detachment fault in the southern Orocopia Mountains.

The Clemens Well fault is part of this system, but it actually denotes a lineament that is a combination of structural elements. It is, in part, an upper-plate normal fault on the southeast and, in part, the DDF to the northwest (figs. 2 & 4). It is not discernible what the normal faults do at depth. These brittle faults might be upper-plate normal faults that truncate into the main DDF at depth or they might be part of a series of progressively younger cross-cutting faults. Data indicate that the microbreccia was formed at 25 Ma and that brittle fault gouge formed until 14 Ma

(M. Shafiqullah, written commun., 1991). Do they bracket a period of continuous extensional deformation? More age data must be obtained to determine the relationship. This late Oligocene to mid-Miocene period of extension is related to the expansion of the Diligencia basin and the deposition of the Diligencia Formation. The offset of structures (fold axes) in the Diligencia basin by normal faults along the Clemens Well lineament indicates that a significant portion of the folding in the basin occurred during or shortly following sedimentary deposition.

The OMDF and the DDF represent extensional deformational episodes that show a progression to more brittle conditions during exhumation of the Orocopia Schist. Together these features, which were produced during Tertiary extension in the Orocopias, are referred to as the Orocopia Mountains Detachment System (OMDS). Diagrammatic cross sections illustrating the structural development of this progression of faults are shown in figure 6.

Details of the Geology

The geology of the Orocopia Mountains is best described by dividing the rocks into their natural structural packages (figs. 2, 3 & 4). The lower plate to the detachment system is represented by the Orocopia Schist (Mos). The upper plate is composed of crystalline rock units (Pcgb, Jmgn, Agn, Ka) that have a complex geologic history, and sedimentary rocks of the structurally and depositionally overlying Diligencia basin (Td1-Td5). A transect from southwest to northeast along cross section A-A', shown in figure 2, provides a profile from the lower plate, through the upper plate and into the sedimentary basin.

<u>Lower Plate: Orocopia Schist</u>

The Orocopia Schist forms the topographically highest portion of the Orocopia Mountains. The schist package has been traditionally drawn as a northwest-trending antiform because of the overall shape of the range. The schist dips to the southwest in much of the range, but reverses the foliation due to a large-scale flexure, or "drag," feature associated with one of the Tertiary normal faults, thus producing the observed antiformal character of the schist package. Recent TM images, however, reveal a more complex antiformal character. The structure of the schist might be better represented by one large and several smaller east-west-trending antiforms that are stacked in a northwest-southeast trend so their axis are truncated by, or plunge below, the OMDS (fig. 5). The dip reversals seen along the southern part of the range that are related to the normal faults appear to be superimposed on the larger-scale antiforms and synforms of the Orocopia Schist.

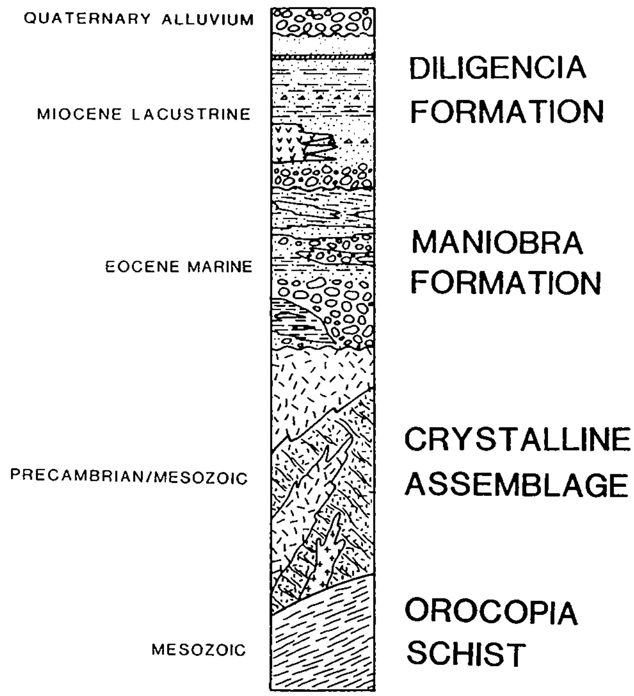

Figure 3. A columnar section of the rock relationships exposed in the Orocopia Mountains. The Orocopia Schist is structurally below a package of crystalline rocks. Eocene marine strata of the Maniobra Formation are unconformably overlain by Miocene lacustrine strata of the Diligencia Formation, which are both depositionally and structurally juxtaposed atop the crystalline package (Crowell, 1975).

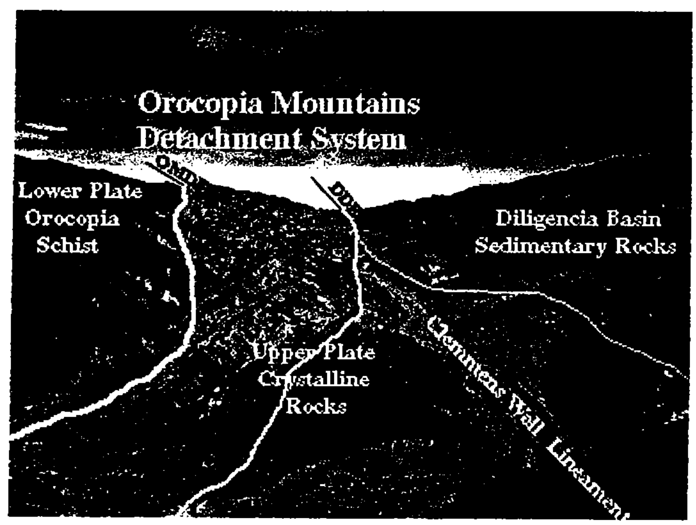

Figure 4. A photograph looking along strike of the Orocopia Mountains Detachment System in the northwest portion of the map area. The Clemens Well Lineament is shown to be a combination of faults. Rocks that are visible include: Mos, is the Orocopia Schist; PCgb, is the banded gneiss; Jmgn is the mafic gneiss; Agn is the augen gneiss; and Ka is the adamellite. The sedimentary rocks of the Diligencia Basin are undifferentiated.

Exhumation of the schist resulted in localized ductile folding. Folds just below the OMDF have axes parallel with the extension lineation of ultramylonite along the OMDF. The ductile fabric was disrupted by brittle deformation that was superimposed on it. Brittle behavior produced zones of fine-grained, intensely pulverized schist that is purplish/blue in color. Normal faults slice up the schist into structurally and mineralogically coherent lenses. This produces an anastamosing pattern of normal faults as imaged in either cross section or map view. The contact with the structurally overlying crystalline package is in part mylonitic, recording the early ductile movement within the fault zone and in part brittle, recording the later, higher-level deformation superimposed on the earlier-formed metamorphic and deformational fabrics.

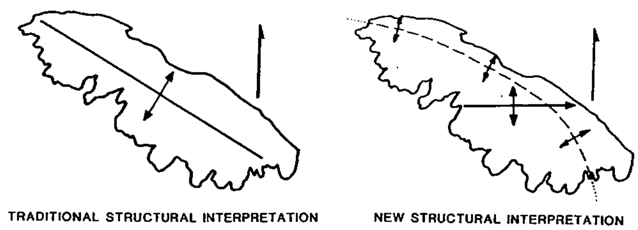

Figure 5. The traditional structural representation of the Orocopia Schist package as a northwest-oriented antiform and a new interpretation based on TM imagery and aerial reconnaissance which depicts an east-plunging antiform with a smaller scale antiformal rollover developed below the upper-plate/lower-plate contact.

Upper Plate: Crystalline Rocks

The rocks above the OMDF have a complex history and are composed of a variety of distinctive rock units (Crowell and Walker, 1962). Several Precambrian crystalline units are present and include older Precambrian units of probable 1.7 Ga age and younger granitic bodies and diabase dikes, as well as Jurassic intrusive units and Cretaceous and Tertiary intrusive units. Precambrian gneiss (L. Silver, pers. commun., 1989) is intruded by a mafic intrusive complex of probable Jurassic age and leuco-granite (Ka) that appears correlative with 79 Ma leuco-granite in the Chocolate Mountains (D. Frost, unpub. work). The gneissic complex consists of syenitic augen gneiss (Agn) and blue quartz banded gneiss (PCgb). This complex is intruded by diorite and gabbro with minor anorthosite (Jmgn).

The upper-plate crystalline rocks have undergone an enormous amount of brittle deformation. There are countless minor shear zones that penetrate and brecciate the upper-plate crystalline complex. Its easily eroded and highly altered character are due to this penetrative brittle deformation.

Upper Plate: Sedimentary Rocks

The contacts between crystalline rocks and sedimentary rocks are both depositional and tectonic. Rocks of the crystalline complex are present in the basal conglomerate of the Diligencia Formation which is developed on irregular basement topography of the crystalline complex in the eastern half of the field area. The Diligencia Formation was clearly deposited on top of the crystalline contact; this contact has been tilted to near vertical positions in much of the basin. The northwest-trending normal fault system truncates the east-west-striking, north-dipping strata along the southwest margin of the basin, which can be seen in the northwest part of the field area. Both the Tertiary rocks and the underlying crystalline rocks are truncated by the extensional fault system. Most of the crustal extent of the detachment system juxtaposes crystalline rock on crystalline rock. Where the Tertiary rocks are involved, however, the relationships are more evident and more photogenic.

Maniobra Formation. Exposed on the northeast side of the Diligencia Basin in Maniobra Valley is a 1500 M marine section that contains fossils of the early and middle Eocene (Cole, 1958; Crowell and Susuki, 1959; Johnston, 1961). The Maniobra Formation consists of brown shales, sandstones, conglomerates and sedimentary breccias deposited on a crystalline basement. Near-shore facies appear to grade into deeper-water facies to the south and southwest. These are temporally correlated with Eocene rocks in the California borderlands. In the Diligencia basin, the Eocene strata define a southwest-dipping horizon which is exposed on the eastern side of the basin and covered down dip to the southwest by Miocene sedimentary rocks of the Diligencia Formation.

Diligencia Formation. The non-marine basal conglomerate of the Diligencia Formation was deposited on an irregular crystalline basement topography in the southwest and unconformably on the Maniobra Formation in the north. The Diligencia Formation is about 1500 M thick (Crowell, 1975). Overlying the basal conglomerate is red/maroon sandstone and siltstone with minor red/ green mudstone and tuff deposits. This sequence is capped by basalt flows dated at 20.6 ± 9.1 Ma, 22.9 ± 2.9 Ma and 19.1 ± 1.9 Ma (Spittler, 1974; Arthur, 1974; Spittler and Arthur, 1982; recalculated using Steiger and Jager, 1977; Dalrymple, 1979) The basalt flows are interfingered with shoreline facies that also contain spring-tufa deposits. These are overlain by mudstone with limestone and minor evaporite. Squires and Advocate (1982) interpret the Diligencia Formation to have been deposited in an east-west trending intermontane valley. Sediment sources were from both the north and the south. The lower portion of the Diligencia Formation was deposited in an alluvial fan environment. This facies grades upward into a braided fluvial facies and then into a shoreline facies.

Subsidence occurred with syntectonic outpourings of basalt. Stratigraphically above the basalt a fluvial deltaic environment records infilling of the lake and the associated fan delta deposits interfinger with deeper water mud and locally developed carbonate layers and evaporite layers (Spittler and Arthur, 1982; Squires and Advocate, 1982).

The sedimentary record in the Diligencia basin is a tape recording of the extensional deformation in the Orocopia Mountains. Basin development began in early to mid Eocene time and this is recorded by the sedimentary rocks of the Maniobra Formation. Basin expansion renewed in late Oligocene time and extension continued through mid Miocene time. This mid-Miocene extensional episode is recorded by sediments of the Diligencia Formation. The timing of deposition is well dated with the interfingering volcanic rocks and is bracketed by age dates on normal faults. It appears that folding of the sedimentary sequence occurred prior to the latest stages of normal faulting around 14 Ma.

Structure

The OMDS is superimposed on the Mesozoic lower amphibolite prograde metamorphism of the Orocopia Schist. Following regional metamorphism, ductile fabric development was by mylonitization. Ultramylonite (Sibson, 1977) along the northwest-striking, northeast-dipping OMDF has microstructures indicating northeast-side-down sense of shear. Extensional lineations in the mylonite dip 10-20 degrees east. Small-scale ductile folds in the schist near the OMDF have fold axes that parallel the stretching lineation. This style of deformation also developed penetrative shear bands that provided pathways for fluids responsible for retrograde metamorphism of the schist. As deformation proceeded, the mylonitic fabric was disrupted by brittle failure and the formation of folds that have sheared off axial surfaces and an associated axial planar, 1-2 cm spaced cleavage. The development of brittle structures effectively excised the ductile fault fabric so the upper-plate/ lower-plate contact is now expressed as a complex zone of anastamosing normal faults. In places, the initial Eocene mylonitic ductile fault contact, the OMDF, is still preserved. This contact is clearly broken by later brittle features forming younger fault contacts, or contacts that are zones of intense cataclasis, such as the DDF. Collectively, these ductile to brittle normal fault fabrics make up the overall Orocopia Mountains Detachment System.

To determine sense of shear across the shear zone, oriented sections were obtained from mylonitic rocks after Simpson (1986), and evaluated using techniques of Simpson and Schmid (1983), Lister and Snoke (1984), and Simpson (1986, 1991). Sections were cut parallel to the lineation and perpendicular to the foliation. Thin sections were studied from a variety of different fault rocks. All sections showed a consistent upper plate to the east sense of movement. Shear-sense indicators (including asymmetric augen, feldspar porphyroclasts with dynamically recrystallized tails, mica fish, shear bands that deflect the primary foliation, microscopic asymmetric folds and quartz subgrain alignment) yield a consistent northeast-side-down sense of shear. The orientation of quartz subgrains is horizontal indicating a vertical axis of shortening.

Microbreccia structures cross cut the ductile mylonitic fabrics. Although no sense of shear was obtained across the brittle cataclastic zones, the offset of hangingwalls to produce half graben sedimentary basins demonstrates the sense of shear across the major brittle fault system. Similar extension is event in nearly all of the neighboring ranges, especially in the ranges to the south along strike of the Orocopias (e.g., Chocolates---Frost and Watowich, 1987; Picacho Peak area---Drobeck and others, 1986). The direction of motion can be deduced from striations on the slickensided surfaces along the upper-plate normal faults. Evidence indicates movement of the upper plate to the east which is parallel to structures formed in the earlier phase of ductile extension. These directions of movement imply about 45 degrees clockwise rotation of rocks during Late Neogene time. This is in agreement with paleomagnetic data on sedimentary rocks in the Diligencia Basin (Luyendyk and others, 1985). Rotating the Orocopia block back counter clockwise 45 degrees aligns the Orocopia extensional vectors with the regional northeast-southwest extension direction typical of Miocene deformation along the nearby Colorado River extensional terrane. It is possible that east-west extension or a transition from southwest to more west-directed extension resulted in a more complicated rotation pattern in the Diligencia basin, especially if there was a component of right-lateral shear during extension or if the sediments were being folded during deposition above tilted hanging wall blocks. Rotation of the Orocopias may also have been accomplished during oroclinal bending of a portion of southern California related to motion within the overall San Andreas transform system.

Regional Extent of OMDS

The OMDF strikes southeast through the field area and is truncated by the DDF, which strikes south as it projects out of the range. The faults dip to the east and appear to project underneath the Chocolate Mountains, continuing the large-scale, antiformal-synformal wave pattern of the fault surfaces. In the southern part of the field area are volcanic rocks, similar to Miocene units in the Chocolates, oriented at 040°, 60° NW. When this plane is projected through alluvium it would appear to truncate into the OMDS, oriented at 025° 45° SE, as it leaves the southern Orocopia Mountains. The upper-plate rocks in the southern Orocopias and in the Chocolate Mountains appear to be blocks that are back rotated into a detachment, which continues southeast

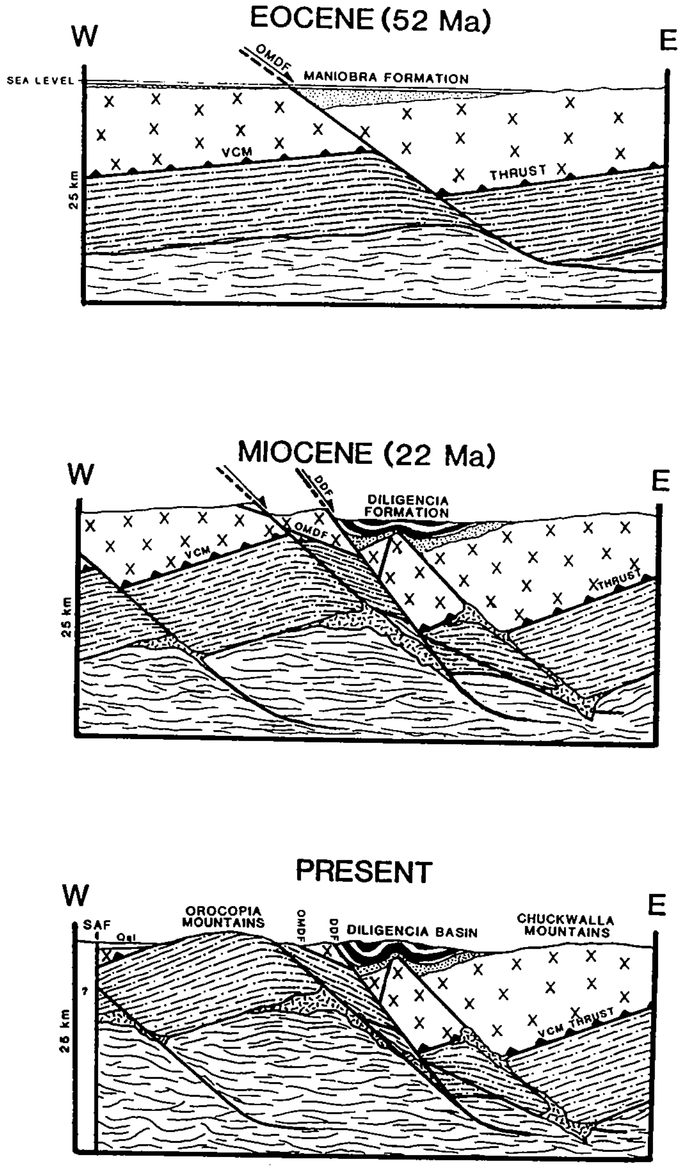

Figure 6. Diagrammatic cross sections depict the tectonic evolution of the Orocopia Mountains. Top; Eocene deformation resulted in partial exhumation of the Orocopia Schist along the ductile Orocopia Mountains Detachment Fault (OMDF), initial formation of the Diligencia basin and deposition of the Maniobra Formation. Middle; Miocene deformation resulted in the complete exhumation of the Orocopia Schist along the brittle Diligencia Detachment Fault (DDF), the deposition of the Diligencia Formation and the development of drape folds above tilted hanging-wall blocks in the Diligencia basin. Bottom; The present structural configuration in the Orocopia Mountains.

around the west side of the Chocolates. In this scenario, the Orocopias are back rotated along an unknown east dipping detachment located to the west, in the Salton Trough, and the Chocolate Mountains are back rotated into the continuation of OMDS as it continues around the west side of the Chocolates. Upper-plate normal faults can be seen on TM images to project across Salton Creek wash and into the Chocolate Mountains without interruption, largely because the crystalline units of the Chocolates and Orocopias are so well differentiated on the TM images. This would rule out a postulated E-W fault in Salton Creek wash having significant displacement. It might also help make some sense of the poorly studied northern Chocolate Mountains.

As the OMDS continues northwest, it is apparently offset to the northwest along the San Andreas and likely continues in the San Gabriel Mountains as the San Francisquito fault along the margin of the Soledad basin or farther to the northwest in the Cuyama basin. Smaller portions of this fault or related extensional features are present in the Crafton Hills area near Redlands and in the southeastern San Gabriel Mountains (Hazelton, 1995).

The timing and style of deformation in the Orocopia Mountains (fig. 6) can be extrapolated to describe, in general, the Tertiary evolution of the Southern California borderlands and the Los Angeles basin (Tennyson, 1988; Robinson and Frost, 1991; Wright, 1993). In the San Joaquin Hills, near Laguna Beach, Eocene and Miocene sedimentary rocks record a similar episode of Tertiary basin development and accompanying Miocene magmatism and deformation (Wright, 1993). The mid-Miocene San Onofre Breccia records the rapid uplift of a metamorphosed subduction complex, probably related to the major detachment faults underlying westernmost California and the California Continental Borderlands (Stuart, 1979; Fattahipour, 1993; Fattahipour and Frost, 1992; Fattahipour and others, this volume; Baker, 1994; Baker and Frost, 1992). In addition to the sedimentary record, north-oriented folds, faults and dikes in the San Joaquin Hills indicate deformation by east-west extension in the mid to late Miocene (Robinson and Frost, 1991).

In both the San Joaquin Hills and the Orocopia Mountains, structures indicate east-west extension and half graben formation in the early and mid Miocene. Extension has exposed the buried pieces of a Mesozoic subduction complex along normal faults adjacent to the major sedimentary basins. Half graben formation and associated block tilting during Miocene extension may have generated zones of crustal weakness that have helped to localize strike-slip faults across southern California. These zones would be the crustal highs of the ductile middle crust present at the close of extension, providing the rheological weakness to localize the major strike-slip faults of much of southern and central California.