MID-TERTIARY EXTENSION IN COASTAL SOUTHERN CALIFORNIA
AS DISPLAYED BY THE HANGING-WALL ROLLOVER
GEOMETRY OF THE SAN ONOFRE BRECCIA

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geological Sciences

by
Mitra Johanna Fattahipour
Spring 1993
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Approved by:
DEDICATION

To Ahmad, Dariush, and Elizabeth.
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CHAPTER I

INTRODUCTION

The term "detachment faulting" was developed from the recognition of low-angle normal faults that characterize the Basin-and-Range province of the western United States. Much of the present understanding of detachment faulting in California is a result of geological studies in the highly extended terranes such as those of southeastern California (Colorado River region), Arizona, Nevada and Utah (Figure 1). In the Colorado River region, Ransome (1931) was one of the first to recognize the presence of low-angle faults but termed them thrust faults. Subsequent studies of low-angle faults in the Colorado River region as well as other portions of the Basin-and-Range provinces have lead to the recognition that these detachment faults are related to a crustal system of brittle and ductile extensional deformation (e.g., Anderson, 1971; Armstrong, 1972; Davis and others, 1980; Frost and Martin, 1982; Howard and John, 1987; Davis and Lister, 1988; Lister and Davis, 1989; Wernicke and others, 1988; Pridmore and Frost, 1992; Frost and Okaya, 1993, in review).

The detachment fault geometries like those defined in the western United
Figure 1. General location map of southern California, Arizona and Nevada. Courtesy of Tom Heidrick, Chevron Petroleum Research Laboratory, La Habra, California.
States are now being recognized in regions of extensional tectonics all over the world (e.g., Henry and Aranda-Gomez, 1992; Pan and Kidd, 1992).

Extension, or rifting, of continental blocks such as the East African rift system and the U.S. Atlantic margin are now being interpreted as a product of detachment tectonics (Wernicke and Tilke, 1989; Bosworth, 1987). With the addition of crustal-scale seismic profiles, the geometries of regional detachment faults have been imaged on nearly every continental margin and have changed the concepts of rifting and basin formation to include major motion on regionally subhorizontal fault surfaces (Etheridge and others, 1989).

In coastal southern California west of the principal strand of the present San Andreas fault system, structural features formed since the Cretaceous have primarily been attributed to transform motion along the San Andreas fault system (Ernst, 1980; Dickinson, 1974, 1980, 1981). Where extensional deformation is clearly present in coastal southern California, it has generally been attributed to wrench faulting associated with strike-slip motion of the San Andreas fault system (e.g., Wilcox and others, 1973; Crowell, 1974, 1987). Strike-slip versus extensional models for the evolution of coastal southern California have previously been discussed (Yeats, 1976), but widely dismissed in favor of transform tectonics by most workers. Robert S. Yeats argued for extension in the California Continental Borderland in 1976 (p. 456): "During
the Miocene, this block was rifted westward away from the continent, exposing the Catalina Schist basement of the SCB [southern California Borderland] by tectonic denudation." However, the strike-slip interpretation of extensional deformation became the accepted paradigm.

The continued refinement of the plate configurations for the Cenozoic and the re-evaluation of some of the structural features in coastal southern California suggest that there was indeed a distinct Miocene extensional event. This deformation occurred contemporaneously with the extensional events of the Colorado River region and other portions of the Basin-and-Range province of the western United States and Mexico.

Unlike the desert exposures within the Colorado River region, the coastal southern California rock exposures are obscured by the presence of vegetation and urban development. In addition to the physiographic differences between these areas, the San Andreas fault system has been active in the past 5 million years resulting in the superposition of transform structures on earlier extensional faults. Hence, strike-slip related faults and deformation need to be recognized in order to unravel any prior structural deformation.

This study re-examines the field relationships between the faulting and deposition within the San Onofre Breccia, which is the primary sedimentological record of the Miocene extensional deformation. Previous
studies on the San Onofre Breccia have primarily focused only on the sedimentological or petrological aspects of this formation (Woodford, 1924, 1925; Stuart, 1975). The observed faults and structures within the San Onofre Breccia have been primarily explained in terms of strike-slip deformation or simply ignored. The re-examination of the faulting and geometry of the San Onofre Breccia indicates a similarity with many extensional features observed in the Colorado River area. The observation of extensional features is explained within a detachment model for coastal southern California that is contemporaneous with that of the Colorado River area.

The interpretation of the presence of regional low-angle normal fault systems that extend the Continental Borderland along an array of east-dipping detachment faults was presented to the geologic community during this and related studies (Fattahipour and Frost, 1991, 1992; Baker and Frost, 1992). The presence of a regional detachment fault system has been verified by regional seismic reflection profiles currently being processed by the U.S.G.S. (e.g., Bohannon and Geist, 1991) and the southern California Earthquake Center (e.g., Legg, 1991; Legg and others, 1991; Crouch and Suppe, 1993, in review).
CHAPTER II

THE SAN ONOFRE BRECCIA: A DESCRIPTION

The San Onofre Breccia was initially described in 1893 by H. W. Fairbanks in the eleventh report of the State Mineralogist. The San Onofre Breccia is exposed primarily on the coast of southern California between Oceanside and Laguna Beach in southern California (Figures 2 and 3; Woodford, 1925). The San Onofre Breccia, or its equivalent, is also exposed in the California Continental Borderland area on Santa Cruz Island, Los Coronados Islands, and in Tijuana, Mexico (Figure 4; Stuart, 1979; Lamb, 1979). The San Onofre Breccia was named after its location on Mount San Onofre, which is presently situated on the property of the marine base of Camp Pendleton (Figure 2).

Fairbanks (1893) and Woodford (1924, 1925) recognized the unusual characteristics of the San Onofre Breccia which were a result of the clast type, size, source and structure. Stuart (1975, 1979) studied the sedimentologic patterns within all of the major locations of the San Onofre Breccia and related those to the plate tectonic models of the time.

The San Onofre Breccia is a formation of Early to middle Miocene age
MCBCP = Marine Corps Base of Camp Pendleton

Woodford (1925).

Figure 2. Main outcrop areas of the San Onofre Breccia.
MCBCP = Marine Corps Base of Camp Pendleton

Source: Piedmont Pacific Trade Company, Southern California from 438 miles in space.

Figure 3. Thematic mapper image of southern California from Laguna Beach to Oceanside.
Modified from Stuart (1979).

Figure 4. Outcrop localities of the San Onofre Breccia.
Figure 5. Subsea "basement" localities of the Catalina Schist and other "basement" rocks.
about 14 to 17 Ma as indicated by foraminiferal stages and strontium isotopic ages of oysters (Stuart, 1975; J. Boles, personal communication with E.G. Frost, 1991). The source of the San Onofre Breccia was a metamorphosed Mesozoic accretionary wedge consisting primarily of the Catalina Schist. The Catalina Schist is exposed on Santa Catalina Island, in the Palos Verdes Hills, in the subsurface of the western portions of the Los Angeles basin and subsea localities in the California Continental Borderland (Figures 4 and 5; Schoellhamer and Woodford, 1951; Stuart, 1979; Sorensen, 1988). The subsea exposures appear to be located along the California Continental Borderland highs, along the Thirty- and Sixty -mile banks and further west to the Patton escarpment (Crouch, 1981; Sorensen, 1988; Wright, 1991; Legg, 1991).

The San Onofre Breccia is composed of a variety of clasts including quartz schist, saussurite gabbro, garnet amphibolite and the distinctive glaucophane greenschist, and blueschists that compose the Catalina Schist as well as Miocene volcanic rocks, reworked Poway-type clasts and some sedimentary fragments (Figure 6; Stuart, 1979; Woodford, 1925). Most of the clasts within the San Onofre Breccia are indistinguishable from its source making the differentiation of the clasts from the source difficult in dredge samples. Although all the subsea Catalina Schist sources have not been correlated to their respective sedimentary deposits, it is clear that the Catalina
Figure 6. Glaucophane greenschist clasts within the San Onofre Breccia.
Schist formed a proximal high relative to the present San Onofre Breccia locations.

The San Onofre Breccia is composed of a variety of clast sizes. The smaller and flatter clasts within the San Onofre Breccia display a well-developed imbrication within the formation. This imbrication indicates primarily a west to east direction of transport from offshore onto the currently exposed landmass (Figure 7; Stuart, 1975; Craig, 1984). The size and distribution of the large clasts within the San Onofre Breccia are indicative of a major tectonic event analogous to those observed in well-studied extensional terranes (e.g., Dickinson, 1991). One of the largest clasts exposed in the San Onofre Breccia is a garnet amphibolite clast measuring approximately 11 meters in diameter (Figure 8; Stuart, 1979; Fairbanks, 1893). Large clasts within the main outcrop area of the San Onofre Breccia are common indicating a source in proximity to its main depositional area (Figure 9; Fairbanks, 1893; Stuart, 1975).

One of the most striking properties of the San Onofre Breccia is that it is tilted generally to the west from approximately 15 to 70 degrees (Figures 10 and 11). The tilting of the San Onofre Breccia was first noted in the observations of the area by H.W. Fairbanks in 1893 and in a cross-section by A. O. Woodford in 1925 (Figure 12). Within a framework of mainly westerly
Figure 7. Photograph of imbrication within the San Onofre Breccia exposed on the marine base of Camp Pendleton indicates a west to east direction of transport.
Figure 8. Photograph of a garnet amphibolite clast within the San Onofre Breccia, measuring 11 meters, located on the Marine Corps Base of Camp Pendleton.
Figure 9. Photograph of a large glaucophane greenschist clast within the San Onofre Breccia located on Laguna Beach.
Figure 10. Photograph of steeply dipping beds of the San Onofre Breccia at Laguna Beach.
Figure 11. Photograph of gently dipping beds of the San Onofre Breccia at Laguna Beach.
dips within the San Onofre Breccia, there is a great range in strike and dip directions. This variability in orientations defines an antiformal and synformal geometry and appears to have affected the facies relationships within the unit (Figure 3). These relationships between structure and stratigraphy will be discussed further within the context of the regional extensional model.

The relationship of the San Onofre Breccia to younger and older sedimentary units can generally be described in relation to the degree of tilting within these units. In the area of the marine base of Camp Pendleton, the tilted San Onofre Breccia overlies similarly tilted rocks of Eocene and older sedimentary formations such as the Santiago Formation (or La Jolla Formation equivalent). In the area of Laguna Beach, the tilted San Onofre Breccia overlies similarly tilted rocks of the Topanga, Sespe and Vaqueros Formations. Unconformably overlying the San Onofre Breccia are the upper Miocene Monterey Formation, the lower Pliocene Capistrano Formation, and younger marine terraces. The unconformity is represented by the less-tilted nature of the Monterey Formation and the subhorizontal nature of the Capistrano Formation and younger marine terraces (Figures 13 and 14; Ehlig, 1979; Woodford, 1925). Locally, in areas on Camp Pendleton and in Laguna Beach, the San Onofre Breccia interfingers with the late Miocene Monterey Formation and the early to middle Miocene Topanga Formation suggesting a gradational
Figure 12. Cross sections from west (E) to East (E') through Mount San Onofre, in the present area of the Marine Corps Base of Camp Pendleton.
Figure 13. Cross-section from San Onofre Mountain to the coast, showing the nature of the more steeply dipping middle-Miocene San Onofre Breccia and Eocene Santiago Formation and the less steeply dipping late Miocene Monterey Formation and subhorizontal nature of the overlying terrace deposits.
Figure 14. Photograph of flat lying terrace deposits overlying the tilted beds of the San Onofre Breccia, Marine Corps Base of Camp Pendleton.
contact between these units (Stuart, 1975; Vedder, 1979). Hence, the structural relationships described for the San Onofre Breccia are transitional in time through the stratigraphic relationships exposed within the rock record of the southern California coastal area.
CHAPTER III

THE NATURE OF FAULTING WITHIN THE SAN ONOFRE BRECCIA

The best exposures of faults within the San Onofre Breccia occur along the sea cliffs, particularly in the Laguna Beach and Dana Point areas (Figures 2 and 15). Two main generations of faults are observed in the main outcrop area of the San Onofre Breccia between Oceanside and Laguna Beach:

1) moderate to low-angle middle Tertiary faults, most of which are normal faults (Figures 15 through 18); and

2) high-angle Pliocene and younger faults, most of which are strike-slip faults (Figure 19).

Striations and mullion structures are well-developed along many of the faults and help differentiate between normal and strike-slip offset.

Jackson (1987) summarized the relationship of the dip of active normal faults from different areas around the earth and concluded that nearly all active normal faults have dips in the range of $30^\circ - 60^\circ$. Seismic data obtained from a wide variety of active normal faults suggest that seismic activity is rarely observed on subhorizontal faults (Smith and Bruhn, 1984; Jackson, 1987). However, since subhorizontal faults are observed in highly extended terranes,
Figure 15. Location of well-developed exposures of moderate- and low-angle middle Tertiary faults truncating the steeply tilted beds of the San Onofre Breccia at Laguna Beach.
Figure 16. Photograph of a moderate-angle middle Miocene fault truncating the San Onofre Breccia at Laguna Beach.
Figure 17. Photograph of a low-angle middle Miocene fault truncating the San Onofre Breccia at Laguna Beach.
Figure 18. Photograph of a low-angle middle Miocene fault truncated by a higher-angle fault in the San Onofre Breccia at Laguna Beach.
Figure 19. Photograph of high-angle Pliocene and younger faults truncating the San Onofre Breccia at Laguna Beach.
subhorizontal faults are probably rotated faults that originally dipped at higher angles (Proffett, 1977; Jackson, 1987). The sedimentary rocks bounded by higher-angle faults constitute fault blocks that consequently rotate upon continued extension and show lower dip angles (Proffett, 1977; Jackson, 1987). Subhorizontal faults may also represent regions of aseismic activity in the brittle-ductile transition zone in the crust while seismic activity occurs along higher angle faults (Jackson, 1987). The rheology of the crust suggests that faults should flatten with depth (Smith and Bruhn, 1984). It appears that low-angle normal faults are more common in the subsurface than in the surface due to differences in brittle-ductile behavior in the crust (Smith and Bruhn, 1984).

The relationship of faulting to bedding angles observed in the San Onofre Breccia indicates that faults that are presently low-angle were once high-angle faults and have since rotated with the bedding. This relationship may be demonstrated by the 'cut-off' angle, the acute angle between bedding and the fault plane. The cut-off angle observed in one of the sea cliff outcrops in Laguna Beach is approximately 60° (Figure 17). Hence, if the San Onofre Breccia is returned to a subhorizontal bedding, this low-angle fault would have an original dip of approximately 60° (Figure 20).

This relationship of progressive flattening of faults with continued extension is not unique. Proffett (1977) recognized the evolution of steep to
Figure 20. Schematic representation of the cut-off angle, and rotation of the low-angle fault by returning the bedding plane to a horizontal position.
low-angle faults with progressive extension in the Basin-and-Range in his study of the Yerington district of Nevada (Figure 21). He observed that the gently dipping faults are the oldest and the steepest faults are the youngest. This relationship indicates that the older, gently dipping faults have since rotated and initially had steep dips. The continued extension in the Basin-and-Range resulted in rotating these older faults and the associated beds shallowing the initial dips of the faults while new faults formed at steep angles (Figure 22; Proffett, 1977; Frost, 1981; Pridmore and Frost, 1992). Continued extension and seismic activity produce additional higher-angle synthetic and antithetic faults (Jackson, 1987), tilting the original subhorizontal bedding. Extensive mining and drilling demonstrated the validity of this model in the Yerington district (Proffett, 1977).

Angelier and Colletta (1983) characterized and quantified the evolution of normal faulting and extension in the Gulf of California, Gulf of Suez and the southern Basin-and-Range province. They observed that for first order normal faults, continued extension commonly resulted in an angle of 45°-70° between bedding and the fault plane (Angelier and Colletta, 1983). Second order normal faults resulted in an 80°-90° angle between bedding and the fault plane (Angelier and Colletta, 1983). This "'pack of cards'" model proposed that
Figure 21. A cross-section showing three phases of normal fault generation in the Yerington District, Nevada. 1 = oldest faults, low angle; 3 = youngest faults, high angle.

Figure 22. The progressive evolution of high-angle planar normal faults to low-angle normal faults. As extension progresses, the fault-bounded blocks as well as the faults, rotate. An overall listric shape is produced as the older fault segments are rotated into a subhorizontal orientation.
motion along large first-order faults becomes difficult due to progressive tilting during extension (Figure 23). In addition to second and third order faults, internal deformation of main blocks occurred to accommodate continued extension and tilting (Angelier and Colletta, 1983).

Faulting associated with middle Tertiary crustal extension in southern California is presently exposed as low- to moderate-angle faults that truncate the San Onofre Breccia and older formations (Figures 16 through 18). These faults may have initially started at higher angles but have been tilted contemporaneously with extensional deformation much like those at Yerington. These low- to moderate-angle faults observed in the San Onofre Breccia are predominantly normal faults and generally pre-date the younger Capistrano Formation and marine terrace deposits.

In addition to low-angle middle Tertiary faults, a variety of moderately dipping faults truncate the San Onofre Breccia (Figure 17). Some of these moderately dipping normal faults are antithetic and synthetic faults that sole into a larger detachment fault system. Many of these antithetic faults seemed to have formed in the late stages of extension, although definitive relationships between different generations of faulting are rarely observed as is typical of most extensional terranes. One example of a low-angle fault truncated by a higher angle fault is found in Laguna Beach (Figure 18).
Modified from Angelier and Colletta (1983).

Figure 23. Evolution of faulting with increasing amounts of extension (a-d).
Not all moderately dipping faults appear to be middle Miocene in age. An exception to a middle Miocene age for the moderately dipping normal faults may be exemplified by the Cristianitos fault (Figure 24). The Cristianitos fault trace at San Onofre State Beach juxtaposes the upper Miocene San Mateo Formation against the Upper middle Miocene Monterey Formation and is clearly truncated by Pleistocene terrace deposits (Figure 24; McNey, 1979a). The Cristianitos fault has been previously attributed to strike-slip deformation along the San Andreas fault system (Ehlig, 1979). It is suggested here that perhaps the Cristianitos fault may have initially formed as an antithetic fault in the later stages of Miocene extension and was re-activated with later strike-slip deformation. Additional chronologic and subsurface studies of the Cristianitos fault are required to better quantify the timing of this fault in relation to Miocene extension.

The faulting that post-dates the lower Pliocene Capistrano Formation and the younger marine terrace deposits is evidenced by primarily high-angle faults, most of which are strike-slip related (Figure 19). These high-angle faults cross-cut the San Onofre Breccia and the younger formations and appear to represent displacement in a different tectonic setting. Strike-slip motion along the San Andreas fault system has occurred since the Pliocene in association with the opening of the Gulf of California (Crowell, 1974; Stock and Molnar,
Figure 24. Photograph of the Cristianitos fault, south of the San Onofre Nuclear generating station.
1988; Atwater, 1989; Legg, 1991). Faulting associated with strike-slip faulting in southern California is presently exposed as high-angle faults that truncate the Quaternary marine terraces and older sedimentary formations.

The growth-fault characteristics within the San Onofre Breccia are indicative of an extensional environment in which the San Onofre Breccia was being faulted and tilted along a series of regional normal faults. Progressive offset on these normal faults produced major tilting of the San Onofre Breccia and flattening, or rotation, of the normal faults to gentle angles. The most widespread dips of the San Onofre Breccia are between $25^\circ$ to $35^\circ$ (Ehlig, 1979; McNey, 1979b), and have resulted in tilting of the once high-angle normal faults to moderate dips of $30^\circ$ to $60^\circ$. Where the San Onofre Breccia is very steeply inclined ($60^\circ$ to $70^\circ$), the originally high-angle faults have been tilted further to angles of $0$ to $10^\circ$. It is in these steeply tilted beds where a second generation of normal faults is interpreted to have formed in order to accommodate the continued extension.
CHAPTER IV

MIDDLE TERTIARY TECTONIC SETTING

Since the recognition of the San Andreas fault as a major strike-slip fault in the 1950's (e.g., Hill and Dibblee, 1953), the structures present in the rocks of coastal southern California have been described as resulting from strike-slip motion on this anastomosing fault system. Extensional deformation in coastal southern California was clearly recognized but attributed to wrench faulting associated with strike-slip motion (e.g., Wilcox and others, 1973; Crowell, 1974). R. S. Yeats (1976) suggested that some of this extensional deformation was due to Basin-and-Range deformation. Yeats' ideas were not treated seriously by most researchers in the region, especially with the advent of plate tectonics and the realization that the San Andreas was a transform plate boundary. The wide acceptance of the transform fault model for southern California (e.g., Wilcox and others, 1973; Crowell, 1974; Crouch, 1981) was understandable because no tectonic model incorporating large-scale extension on a plate tectonic setting had been suggested for any of this region. The "accepted wisdom" for the tectonic development of coastal California thus became one of strike-slip disruption of a Mesozoic accretionary and convergent
margin sequence. Hence, even extensional structures of Oligocene or early Miocene age were interpreted as secondary structures within a strike-slip system, long before the late Miocene-Pliocene inception of the San Andreas transform motion (e.g., Bohannon, 1975).

The tectonic setting of southern California during the middle Tertiary is critical to understanding how and why crustal extension occurred. Plate tectonic reconstructions for the western United States in the middle Tertiary indicate that the Farallon slab which was subducting below the Oligocene-Miocene arc, was physically disintegrating due to its relatively young age, high temperature and low strength (Severinghaus and Atwater, 1990). The nearly complete disintegration of the slab by 20 million years ago, resulted in a "slab gap" in the region of present southern California (Figures 25 and 26; Severinghaus and Atwater, 1990).

In the absence of a down-going slab, hot mantle and asthenospheric material flowed into contact with the upper crust of the North American plate. The "slab gap" appears to have resulted in the crustal extension and tilting of the Mesozoic-Tertiary accretionary wedge-subduction complex which constituted much of the crust in western California and the Continental Borderland region (Figure 25).

The strength of the strongly layered crust may explain the tensile forces
Figure 25. Plate configuration and inferred position of the subducting slab underlying North America at approximately 20 Ma. Note the region of "no slab", much of which is presently southern California.
Figure 26. Schematic evolution of the Continental Borderland Extensional Detachment System.
necessary to create extensional deformation in the upper crust (Morgan and Golombek, 1984; Smith and Bruhn, 1984; Kusznir and Park, 1987). In the quantitative model of Kusznir and Park (1987), the lithospheric strength of the continental crust is principally controlled by crustal composition, crustal thickness and the geothermal gradient. By examining the strength of the crust during the elastic, plastic and brittle behavior of the lithosphere, Kusznir and Park (1987) demonstrated that the geothermal gradient is the strongest controlling factor in crustal deformation. An increase in the geothermal gradient decreases the strength of the lithosphere and allows for significant extension. Significant extension occurs when the elastic strength of the middle crust is degraded by plastic flow of hot, lower- to middle- crustal material (Gans and others, 1988; Wernicke, 1986).

As stress cannot be maintained within the ductile or fluidly deforming middle crust, the stress is transferred upward to the upper crust. This stress amplification steadily increases the stress levels developed during middle-crustal deformation by ductile creep until the stress levels are high enough to propagate a rapid strain event, or earthquake. Hence, the lithosphere and crust in the coastal southern California region began to extend as a result of the higher geothermal gradient caused by the "slab gap". The upper-crustal expression of the increase in geothermal gradient in southern California was the
formation of a series of tilt blocks and half-grabens along a series of regional normal faults or detachment fault surfaces (Figures 26 and 27).

As envisioned in this process of crustal extension, by approximately 15 Ma, the Catalina Schist portion of the subduction complex along with the relatively weak edge of the Peninsular Ranges batholith, was exhumed from beneath the main mass of the Peninsular Ranges batholith (Figures 26 and 27). The Catalina Schist was thus exposed as a footwall high west of the relatively strong beam formed by the batholith. The Catalina Schist footwall high shed detritus generally to the east forming the San Onofre Breccia by middle Miocene time. A linked system of normal faults appears to have produced a similarly linked series of half-graben basins into which several Oligocene to middle Miocene sedimentary units were deposited (Figure 27). Where the source terrane was the distinctive blueschist-greenschist Catalina Schist, the equally distinctive San Onofre Breccia was formed. Where the source terrane was upper-crustal batholithic or metamorphic rocks, units such as the Vaqueros Sandstone and Topanga Formation were produced within this extensional tectonic setting.
Figure 27. A schematic East-West cross-section showing Miocene extensional geometries in coastal southern California.
Miocene Volcanism

Major volcanism occurred within southern California during the same time as the deposition of the San Onofre Breccia (Stuart, 1975). Two stages of volcanism have been recorded in southern California on the basis of their chemistries and ages (e.g., Hawkins, 1970; Wright, 1991). Many of these volcanic rocks exhibit a complex chemistry, suggesting that they are not simply arc-derived volcanic materials (Weigand, 1982), which would be characteristic of simple derivation from melting of the down-going slab.

An early episode of late Oligocene-early Miocene volcanism occurred as indicated by volcanic rocks in the western edge of the Continental Borderland, north of the Los Angeles basin as well as in the Mojave desert (Weigand, 1982; Howell and others, 1987; Wright, 1991).

A second major period of volcanism occurred from 17 to 12 Ma and forms abundant flow units throughout the Los Angeles basin and the California Continental Borderland, an area of approximately 60,000 square kilometers (Eaton, 1958; Stuart, 1975; Legg, 1991). Abundant sub-sea exposures of these volcanic sequences are associated with major fault traces which served as conduits for igneous intrusions (Eaton, 1958; Stuart, 1975). Many of these volcanic units occur throughout the California Continental Borderland and appear to cover most of middle Miocene sedimentary rocks such as the San
Onofre Breccia and its associated faults. Exposures of this relationship of thick and widespread volcanic rocks overlying the San Onofre Breccia are seen on Santa Catalina Island and Santa Cruz Island (e.g., Weaver and others, 1969; Forman, 1970; Baker, 1993).

The primary exposures of volcanic rocks occur (Figure 28; Wright, 1991; Shelton, 1953): a) in the Santa Monica Mountains, the Conejo Volcanics, approximately 14 to 16 Ma, unconformably overlying the Topanga Formation; b) in the Santa Monica Mountains, the Zuma Volcanics, early to middle Miocene in age, interfingers marine sandstones similar to the San Onofre Breccia; c) in the vicinity of the San Joaquin Hills, a volcanic breccia within the Topanga Formation approximately 15 Ma and the El Modeno Volcanics, approximately 14 Ma; d) northeast of the Los Angeles Basin, the Glendora Volcanics, interfingering early to middle Miocene Topanga Formation; e) in the Palos Verdes Hills, sills intrude early to middle Miocene Monterey Formation. In addition, subsurface drilling has encountered similar volcanic and several igneous intrusive rocks. Some of these intrusive rocks in the Los Angeles Basin are associated with the Whittier fault zone, and the Inglewood faults. The age of these intrusive rocks tends to be younger than the volcanism, approximately 13 to 9 Ma (Wright, 1991). Definitive work relating the tectonic setting and volcanics of the coastal Californian region is
Figure 28. Location of Miocene volcanic activity in the Los Angeles area.

Weigand (1982).
lacking.

Overlying these older volcanic rocks are thick exposures of more basaltic materials that represent both a distinctly different origin and tectonic setting. In northern Baja California, thick exposures of basaltic rocks form much of the sea cliffs and coastal region from Tijuana to Ensenada (Minch, 1967; Gastil and others, 1975). These volcanic rocks are younger than the widespread volcanic units in the Borderland and appear to be indicative of an origin from a mantle source. The orientation of dikes associated with these flows, may be analogous to the changes in stress orientations observed in the Basin and Range province (see Zoback and Thompson, 1978). Feeder units such as 'dike rock' near Scripps pier in San Diego are oriented north-south and fit the classic model for the San Andreas stress system (e.g., D.U. Wise, 1967).

The Miocene volcanic rocks suggest that the crust in southern California was being extended and thinned during this time. The presence of 24 Ma volcanic rocks may be indicative of the beginning of the extensional deformation in southern California. Gans and others (1989) presented a two-dimensional model depicting the role of magmatism in the extensional environment of the Basin and Range province (Figure 29). The first stage of extension is the result of a thermal weakening of the crust, followed by a series
Figure 29. A model for the Cenozoic tectono-magmatic evolution of the Basin and Range province.
of volcanic eruptions, faulting, and progressive tilting (Gans and others, 1989; Figure 29). It is suggested that like in the Basin and Range, the Miocene volcanism in coastal southern California was part of the extensional deformation caused by the 'no slab' zone and thinned upper crust.
CHAPTER V

THE EXTENSIONAL MODEL FOR COASTAL SOUTHERN CALIFORNIA

Two-dimensional Extensional Deformation Models

Two-dimensional models of extensional deformation are generally discussed in terms of two end-member fault geometries: planar and listric faulting (Wernicke and Burchfiel, 1982; McClay and Ellis, 1987). In the extensional deformation models involving planar fault geometries, both the faults and the beds rotate with continued crustal extension (Wernicke and Burchfiel, 1982; Figure 30). This planar fault model is typically termed the domino-style or 'pack of cards' extensional model (Angelier and Colletta, 1983; Walsh and Waterson, 1991). A variation to this planar fault geometry model is the "soft-domino fault model" where the "variable displacement on individual faults is accommodated by heterogeneous ductile strains" (Angelier and Colletta, 1983; Walsh and Waterson, 1991; Figure 31). In the soft-domino model, internal deformation within the block allows the block to fill the voids that would be created within a completely rigid domino model (Walsh and Waterson, 1991).

In the extensional deformation models involving listric fault geometries,
Figure 30. A schematic diagram of planar and listric normal faults.
Figure 31. A schematic block diagram of the soft-domino fault model. Strain ellipses on the side of the block show the ductile strain for the block as a whole, accommodated by structures which are too small to be represented on this diagram.
the faults may remain stationary or rotate as the beds rotate with continued crustal extension (Proffett, 1977; Wernicke and Burchfiel, 1982; Pridmore and Frost, 1992; Figure 30). One major difference between these two types of models is tilt of the bedding plane in the hanging wall. In the listric fault models, the bedding dips display steeper tilts in the direction of greater downthrow (Wernicke and Burchfiel, 1982). Most extensional terranes appear to contain both domino arrays and listric faults, so that each fault must be examined to see its domino or listric identity. The realization that most extensional terranes contain both listric and domino faults has led to the use of the term "mixed mode extension" and appears to be the worldwide general model of extensional deformation (Tom Heidrick, 1992, personal communication).

An additional complexity to the listric fault model occurs with the placement of a ramp-and-flat detachment surface (Gibbs, 1984; Figure 32). The presence of a ramp- and-flat geometry in the footwall will produce associated hanging-wall anticlines and synclines in the hanging-wall with continued extension (Figure 32). The concept of a hanging-wall rollover previously termed "reverse drag" has been observed in highly extended terranes such as the Colorado Plateau and the North Sea (e.g., Hamblin, 1965; Gibbs, 1984). The hanging-wall rollover geometry may also produce a series of
Figure 32. The ramp and flat geometry of a detachment surface and the associated hanging wall rollover.
listric, antithetic faults that dip in the opposite direction of the synthetic faults (e.g., Hamblin, 1965; Gibbs, 1984; Figure 33).

The sequential development of normal faults in the Basin-and-Range province typically demonstrates the relationship between the age and dip of normal faults (Proffett, 1977; Frost, 1981; Figures 21 through 23). This relationship is discussed in the chapter on the faulting observed in the San Onofre Breccia and re-emphasized here. Continued extension results in tilting of faults and bedding and the propagation of new faults at higher angles. Hence, extensional terranes typically show a series of moderate to 'flat' dipping faults indicative of progressive faulting and extension (Pridmore and Frost, 1992).

**Extension in coastal southern California**

The two-dimensional deformational models form the basis for the middle Tertiary extensional model of coastal southern California presented here. On a large scale, southern and Baja California, are a tilted crustal slab and have similar cross-sectional geometries along their entire length. As a first approximation, the crustal deformation can be examined in a two-dimensional sense for ease of discussion. In more detail, the extension is clearly three-dimensional in its configuration and will be discussed following the review of
Figure 33. A schematic diagram showing synthetic and antithetic faults.

the two-dimensional geometries.

In the extensional model for coastal southern California, the San Onofre Breccia represents the hanging-wall rollover on the western edge of the Peninsular Ranges batholith (Figure 27). By the middle Tertiary, a series of Borderland domino arrays were present west and east of the Peninsular Ranges batholith forming a series of half-grabens and sedimentary basins. The Peninsular Ranges batholith acted as a resistant beam and an intact block while regional normal fault blocks were tilting and faulting on each side during middle Tertiary extension. The eastern boundary of the Peninsular Ranges batholith is represented by the Salton trough detachment system and the western boundary is termed the California Continental Borderland detachment system (Figure 27; Blom and others, 1988; Frost and others, 1993).

The San Onofre Breccia records major middle Tertiary extensional deformation and syn-tectonic sedimentation in southern California. The geometry of the San Onofre Breccia aids in identifying the occurrence of ramp-and-flat geometries within a larger detachment fault system within southern California. Two schematic cross sections are drawn from the Elsinore fault zone to the Continental Borderland through Camp Pendleton and Laguna Beach depicting the two-dimensional extensional structures prior to San Andreas faulting (Figures 34 and 35). In both these cross sections, the fault blocks or
Figure 34. A schematic cross-section from the Elsinore fault zone to the Continental Borderland, through Camp Pendleton during the Miocene.
Figure 35. A schematic cross-section from the Elsinore fault zone to the Continental Borderland, through Laguna Beach during the Miocene.
domino arrays west of the Peninsular Ranges batholith are generally controlled by planar faults that sole into the underlying detachment fault or faults. However, the half-graben containing the San Onofre Breccia hanging-wall rollover structures is probably controlled by a listric fault that soles into the underlying detachment fault. The presence of a major rollover, or bend in the shape of the hanging-wall from near horizontal to steeply dipping, indicates that the fault shape must be listric (Figures 34 and 35). Elsewhere in the Borderland, the blocks appear to be simple tilt blocks, suggesting more of a domino fault shape. The Borderlands is thus like many other extensional terranes in being "mixed mode". The overall listric fault shape is probably controlled by the shape of the coherent beam of the Peninsular Ranges batholith to its east.

The presence of early Tertiary sedimentary deposits underlying the San Onofre Breccia containing a batholithic source suggests the presence of a batholithic source to the west as well as to the east prior to the early Miocene. Hence, a batholithic portion of the Peninsular Ranges batholith was exhumed from beneath the main mass of the Peninsular Ranges batholith during the process of early and middle Tertiary extension (Figures 34 and 35). However, this western batholithic source was depleted by the middle Miocene with the deposition of the San Onofre Breccia, which is almost exclusively composed
of the clasts of the accretionary wedge rocks that were structurally below the batholith. The faulting observed within the San Onofre Breccia indicates that sedimentation of the San Onofre Breccia was contemporaneous and synchronous with progressive faulting and extension offshore. The San Onofre Breccia represents only the sedimentary record of a blueschist-greenschist source, while the timing of Tertiary extension probably began prior to 17 Ma, the early age of the San Onofre Breccia (age from J. Boles, 1991, personal communication with Eric Frost). The middle Tertiary extension is also recorded in units such as the Vaqueros Sandstone, Simmler Formation and perhaps even the Sespe Formation (e.g., Nilsen, 1987).

The hanging-wall rollover geometry of the San Onofre Breccia in the Camp Pendleton and Laguna Beach areas demonstrates the presence of a ramp and flat geometry of the underlying "basement" rocks of the Catalina Schist and the Peninsular Ranges batholith (Figure 34 and 35). The hanging-wall rollover geometry of the San Onofre Breccia is most pronounced in the Laguna Beach area where the steeply dipping beds and flat faults are observed. In the Laguna Beach area, the San Onofre Breccia forms the crest of an antiform in the Laguna Beach area and forms the synform between the San Joaquin Hills and the Santa Ana Mountains (Figure 35). This pronounced hanging-wall rollover geometry suggests: 1) the detachment fault is closer to the surface
offshore of Laguna Beach than in the Camp Pendleton area, and 2) a pronounced ramp and flat structure may exist underneath the San Joaquin Hills in the Laguna Beach area.

This simplistic description of the crustal structure of coastal southern California may serve as a model for understanding the greater detailed complexities of the sedimentary deformation that resulted from later San Andreas transform faulting. Seismic lines shot in the region in the last several years, indicates that this model of crustal extension may be widely applicable throughout the Borderland (e.g., Bohannon and others, 1992; Legg, M., 1992, personal communication with Eric Frost).

It appears that much of the middle Tertiary extension in the coastal southern California may be contemporaneous with the middle Tertiary extension in southeastern California and Arizona. Pliocene and younger strike-slip motion has since laterally displaced the middle Tertiary tilt blocks and half-grabens.

**Three-dimensional Models**

The two-dimensional cross-sections through the Camp Pendleton and Laguna Beach areas (Figures 34 and 35) must be placed in the context of three-dimensional geometries observed in present geologically active extensional
systems. The east African rift system is a recent analogue of extension that may be correlated with extension in coastal southern California. Bosworth (1987) in his study of the Gregory rift segment of the east African rift system, suggested that rifting or extension occurs in asymmetrical half-grabens. In addition, the east African rift commonly demonstrates a sinusoidal geometry in map view (Figure 36; Bosworth, 1987; Wernicke and Tilke, 1989). These same geometries have been observed in the central Atlantic margin as indicated by the sinusoidal geometry of the coast of the eastern United States (Figure 37; Wernicke and Tilke, 1989).

A thematic mapper image of southern California displays the sinusoidal outcrop pattern of the San Onofre Breccia (Figure 3). This sinusoidal outcrop pattern may be indicative of the shape of the underlying detachment surface offshore of the San Onofre Breccia outcrops. Although our comparison with the east African rift or the U.S. Atlantic margin involves a vastly different scale, it is assumed that these geometries may be seen at various crustal scales. Experimental clay models of extension have demonstrated the presence of a sinusoidal fault pattern during extension (e.g., Cloos, 1968), as a general mechanism for normal faulting, especially on a sphere.

A sinusoidal geometry of the detachment surface and the associated hanging-wall geometry of the San Onofre Breccia may explain the various
Figure 36. Map view representation of the sinusoidal geometry of the East African Rift.
Figure 37. A schematic block diagram of the sinusoidal geometry of the eastern margin of the United States.

facies changes present in this unit. It would be expected that a facies change would occur between Catalina Schist debris being deposited on the crest and the troughs of the fault scarp (Figures 38 and 39). The facies changes between the different outcrop units in the San Onofre Breccia have been described by Stuart (1975) but have not been correlated with a sinusoidal fault geometry.

Extension and sedimentation along a synformal and antiformal fault geometry as recorded by the San Onofre Breccia appears to concentrate larger clasts near the antiform and smaller clasts near the synforms (Figure 39). However, reverse geometries are also plausible. Sedimentation patterns in modern day analogues such as Death Valley may aid in determining the present complexities. A re-examination of the detailed sedimentologic patterns within the San Onofre Breccia is beyond the scope of this study. However, in this generalization of fault geometries and deposition, the shape of a sinusoidal fault would undoubtedly play a significant role in the sedimentation of the San Onofre Breccia.

Linked Normal Faults and Transfer Faults

The term "linked normal fault system" generally refers to the three-dimensional continuity of listric faults (Figure 40; e.g., McClay and Ellis, 1987; Gibbs, 1984; Roberts and others, 1990; Walsh and Waterson, 1991).
Figure 38. A schematic block diagram showing the sinusoidal geometry of the detachment fault surface and the deposition of the San Onofre Breccia.
Figure 39. Map view representation of the Continental Borderland detachment system.
Roberts and others (1990).

Figure 40. A block diagram showing a linked normal fault system in the North Sea.
Associated with a linked normal fault system are a series of transfer faults and fault bridges which accommodate the non-linear offset of the extensional deformation, making it possible to transfer slip from one portion of one fault to another linked fault. A transfer fault is not to be confused with a strike-slip fault as it may contain more of a dip-slip component (Figures 41 and 42; Roberts and others, 1990). A schematic block diagram showing the fault patterns and displacement geometries in the North Sea may be analogous to the middle Tertiary extensional deformation in coastal southern California. In examining detachment fault systems, the concept of linked normal faults is important in that it emphasizes the different "steps" or breaks that may occur along a detachment fault system. These fault geometries would affect the depositional patterns of overlying sedimentary rocks.

**Implications for the Los Angeles Basin**

One of the largest such basins created during this extensional deformation was the Los Angeles basin. Cross-sections from the Patton escarpment to the Los Angeles basin demonstrate that the original formation of the Los Angeles basin was as a series of extensional half-grabens (Campbell and Yerkes, 1976; Wright, 1991; Figure 43). Traditionally, basin formation in southern California has been attributed to wrench faulting associated with
Figure 41. A block diagram showing a normal fault with normal slip (Sn) and an oblique transfer fault with oblique slip (So).
Figure 42. A block diagram showing a) "relay-ramp" developed between two enechelon normal faults; b) collapse of a relay ramp into a transfer fault after increased extension.
Campbell and Yerkes (1976); modified by Wright (1991).

Figure 43. Cross-section from the Patton escarpment through the Los Angeles basin depicting a series of tilt blocks and half-grabens.
San Andreas related right-lateral transform motion. The interpretation of basin formation in southern California presented here suggests that a different tectonic setting was responsible for the original late Oligocene to early Miocene development of the basins prior to their disruption and dismembering by the San Andreas system. In the interpretation presented here, later strike-slip deformation superimposed additional faults upon an earlier extended upper crust, deforming the basin in middle Miocene through Recent times.

In this extensional model of coastal southern California, the Palos Verdes Peninsula, composed of the Catalina Schist, represents the footwall high to the Los Angeles basin hanging wall. A modification to a cross-section through this area published by Wright (1991), suggests how this extensional model can be projected to areas in coastal southern California (Figure 44). Smaller half-grabens further segment the basin and are defined by major sedimentary thickness variations within the synorogenic basin deposits (Figure 44; see Wright, 1991). Later strike-slip faulting may well have been localized along the attenuated portions of the crust and allowed segmentation of the extensional complex by Pliocene transform motion. Facies patterns and thickness variations within the early Miocene as depicted by Wrights’ detailed cross sections, display the original half-graben shapes of portions of the basin prior to overprinting, or inversion, by strike-slip faulting.
Figure 44. Modifications to a Los Angeles basin cross-section by Wright (1991) using an extensional deformational model.
The Newport-Inglewood fault zone has been considered to have had a "long and complex history as a zone of crustal weakness that has responded in a different way to each of a shifting sequence of stress fields" (Campbell and Yerkes, 1976). The extensional model presented here suggests that the Newport-Inglewood fault zone was a synthetic fault that soled into a lower middle Miocene detachment fault system and has since been reactivated by transform faulting (Figure 44). The Palos Verdes fault zone may have a similar history but may represent a reactivated antithetic fault that soles into a lower middle Miocene detachment fault system (Figure 44). Numerous other structural features within the Los Angeles basin may be reinterpreted within the context of an extensional detachment fault model that predates the San Andreas formation.
A re-examination of fault geometries within the San Onofre Breccia suggests at least two generations of faults: 1) moderate- to low-angle faults and 2) high-angle faults. The presence of low-angle normal faults truncating the San Onofre Breccia suggests that these faults were originally formed at higher angles and have since flattened with progressive tilting and contemporaneous sedimentation during middle Tertiary extension. The second generation of high-angle faults truncate the San Onofre Breccia and younger sedimentary rocks. Mullion structures on these high-angle faults suggest a strike-slip tectonic history.

In the extensional deformation of southern California presented here, the San Onofre Breccia represents the hanging-wall rollover along a corrugated ramp-and-flat detachment fault system. A series of linked normal faults extended the western edge of the Peninsular Ranges. The San Onofre Breccia formed in a half-graben constrained by a Catalina Schist footwall high to the west and the Peninsular Ranges to the east. This extensional model of coastal southern California is analogous to the extensional models presented for the
highly extended terranes of the Basin-and-Range province. The hanging-wall rollover geometry of the San Onofre Breccia suggests that one of the California Borderland detachment faults lies directly offshore. The linked arrays of normal faults continue into the California Continental Borderland.

It appears that San Andreas strike-slip motion probably truncated middle Tertiary detachment faults where the crust was the thinnest. Strike-slip motion then laterally transported the tilt blocks and half-grabens northward away from the adjacent sedimentary half-grabens.

The tectonic setting necessary to create such structures may be explained by the middle Tertiary "slab gap" created in the area of present southern California (Severinghaus and Atwater, 1990). A dying slab under coastal southern California may have resulted in rising the geothermal gradient resulting in extension in the upper crust as hot and relatively mobile mantle and asthenosphere moved beneath the crust of southern California.
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ABSTRACT
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During the middle Tertiary, much of the western United States, including coastal southern California and the Continental Borderland underwent crustal extension. The sedimentologic record of this extension is recorded by the San Onofre Breccia, which is an alluvial fan composed primarily of greenschist- and blueschist- facies clasts derived from the Catalina Schist. The flat to steeply tilted nature of the San Onofre Breccia and the older Eocene sedimentary units indicate the presence of hanging-wall rollovers and synorogenic sedimentation during middle Tertiary extension. Gently inclined normal faults cut the steeply tilted San Onofre Breccia and appear to have facilitated the regional exposure of blueschist- and greenschist- facies rocks during progressive tilting of both the Mesozoic accretionary wedge and the thinned western edge of the Peninsular Ranges batholith. High-angle normal and strike-slip faults cut the San Onofre Breccia and overlying younger formations, indicating that several generations of faulting have affected the San Onofre Breccia region after the first-formed faults produced the San Onofre Breccia basin.

By the early Tertiary, Mesozoic accretionary wedge rocks were
positioned 'stratigraphically' beneath the western margin of Mesozoic arc rocks of the North American plate. By the middle Miocene, an array of linked normal faults extended this relatively thin, wedge shaped western edge of the Peninsular Ranges and related arc rocks. Such extension exhumed the Catalina Schist portion of the subduction complex from beneath the Peninsular Ranges batholith and created a series of tilt-blocks and half-grabens into which the San Onofre Breccia was deposited. This array of linked normal faults extended the crust outboard of the current coast of southern California, affecting most of the 70,000 square kilometers of the Continental Borderland.

The timing and geometry of middle Tertiary crustal extension in the Continental Borderland suggest that it is a reflection of slab disintegration below the Oligocene-Miocene arc as the last remnants of the hot Farallon plate were subducted beneath this portion of western North America. This slab disintegration and resulting motion within the mantle and asthenosphere produced an array of regional normal faults that strongly extended the more brittle, but passively deforming upper crust. The Peninsular Ranges batholith acted as a strong, coherent beam separating regional normal faults that bracketed both the eastern and western sides of the batholith and allowed it to remain a nearly intact block during the Oligocene-Miocene extension.

Attenuation of the crust during middle Tertiary extension appears to
have strongly influenced the geometries of the late Miocene and Pliocene San Andreas transform system. Attenuation of the crust produced by normal faulting appears to have created large-scale, upper-crustal anisotropies that strongly localized the geometries of the later strike-slip faults. The moderately to gently inclined normal faults are cut and laterally offset by the mostly high-angle strike-slip faults. The Miocene extensional geometries thus provides critical piercing points within the Pliocene strike-slip system.