

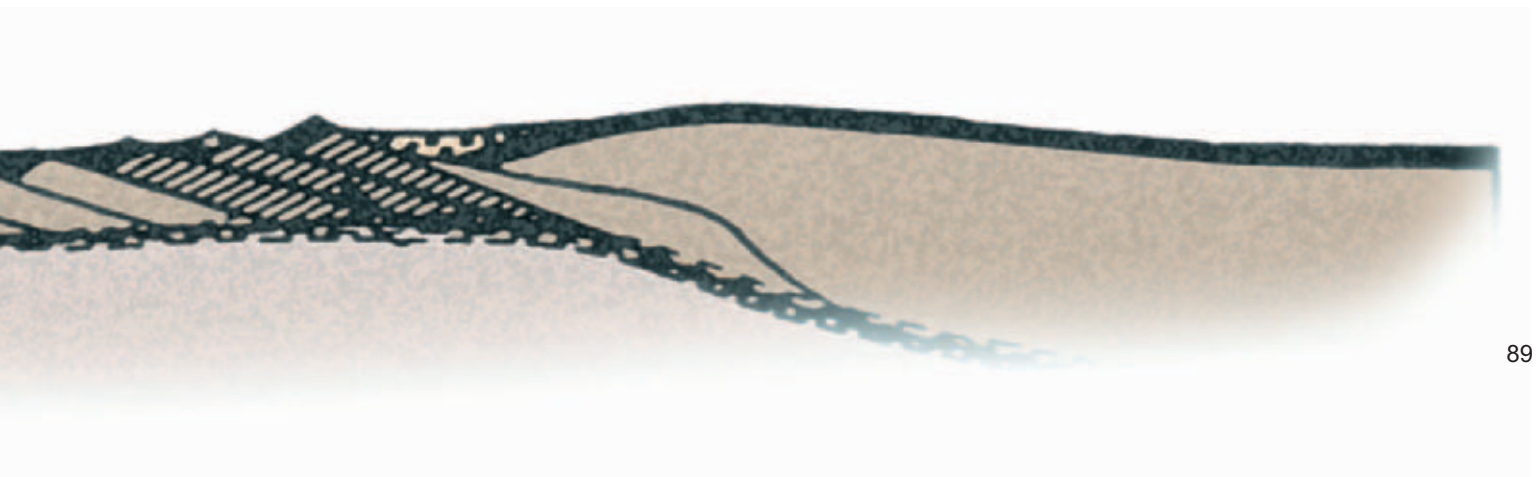
5 Stratigraphy, Tectonics, and Basin Evolution in the Anza-Borrego Desert Region



*The most beautiful thing
we can experience
is the mysterious;
It is the source of all true art
and all science.*

Albert Einstein

Rebecca Dorsey



Stratigraphy, Tectonics, and Basin Evolution in the Anza-Borrego Desert Region



Southern Borrego Badlands Looking West. (Photograph by Rebecca Dorsey)

Introduction

The fossil record of past life is commonly preserved in ancient sediments and sedimentary rocks. Sediments accumulate in subsiding basins that contain different kinds of depositional environments such as rivers, lakes, deltas, and marine seaways. These environments are friendly to life, and often support assemblages of plants and animals. Through integrative studies of stratigraphy, sedimentology, and paleontology, we can reconstruct ancient life communities and the environments in which they lived.

Plate tectonic forces determine where sedimentary basins form, how long and how fast sediments accumulate, and how they may later be faulted, uplifted, and eroded at the surface. Climate also affects basins and sediments; precipitation, wind, and temperature variation affect surface processes such as erosion and soil formation. In the Salton Trough region of southern California, styles, rates, and environments of basin formation have evolved through time in response to complex changes in driving tectonic forces, fault interactions, and climate change. Because of the rich history of geologic research in Anza-Borrego Desert State Park and adjacent areas, it is impossible to summarize all of the knowledge on this subject in a few pages. This chapter presents a brief overview of existing knowledge about the regional stratigraphy, tectonic evolution, and major sedimentary basins preserved in the Park, which have supported a great diversity of plants and animals during the past ~10 million years.

Anza-Borrego Desert State Park is located within a complex zone of strike-slip faulting and oblique crustal extension and compression that defines the tectonically active boundary between the North American plate and the

Pacific plate in southern California (Figures 5.1, 5.2). The southern San Andreas fault system, which includes the San Andreas, San Jacinto, and Elsinore faults, is a broad zone of past and ongoing seismic activity that separates areas belonging to the Pacific plate (Baja California and southern California) from areas located on North America (mainland Mexico and the U.S.). Long-term northwesterly movement of the Pacific plate relative to North America has resulted in progressive right-lateral fault displacements and related crustal deformation during the past ~25 to 30 million years, producing a complicated network of faults, rotating crustal blocks, mountain ranges, and sedimentary basins. The two plates are also diverging slightly in some areas, which has caused the Salton Trough and Gulf of California to open up by oblique rifting and extension during the past 10 to 15 million years. These aspects of relative plate motion and the development of geologic structures on a regional scale are known from landmark studies by Atwater (1970), Lonsdale (1989), Stock and Hodges (1989), Powell et al. (1993), DeMets (1995), Dickinson (1996), Atwater and Stock (1998), Axen and Fletcher (1998), Oskin and Stock (2003), and others.

As described below, we now know that regional subsidence related to crustal extension and transtension (a combination of strike-slip movement and oblique extension of a fault) produced a number of fault-bounded basins that filled with sediments from Miocene to Pleistocene time (Figures 5.2, 5.3, 5.4). In the recent geologic past (last 1 to 2 million years) many of these basins have been uplifted and eroded to reveal the diverse stratigraphic record of their tectonic, climatic, and paleontologic evolution. In the Salton Sea, fault-controlled subsidence has continued to the present day, accumulating a thick section of young sediments that are buried in the modern basin beneath the surface.

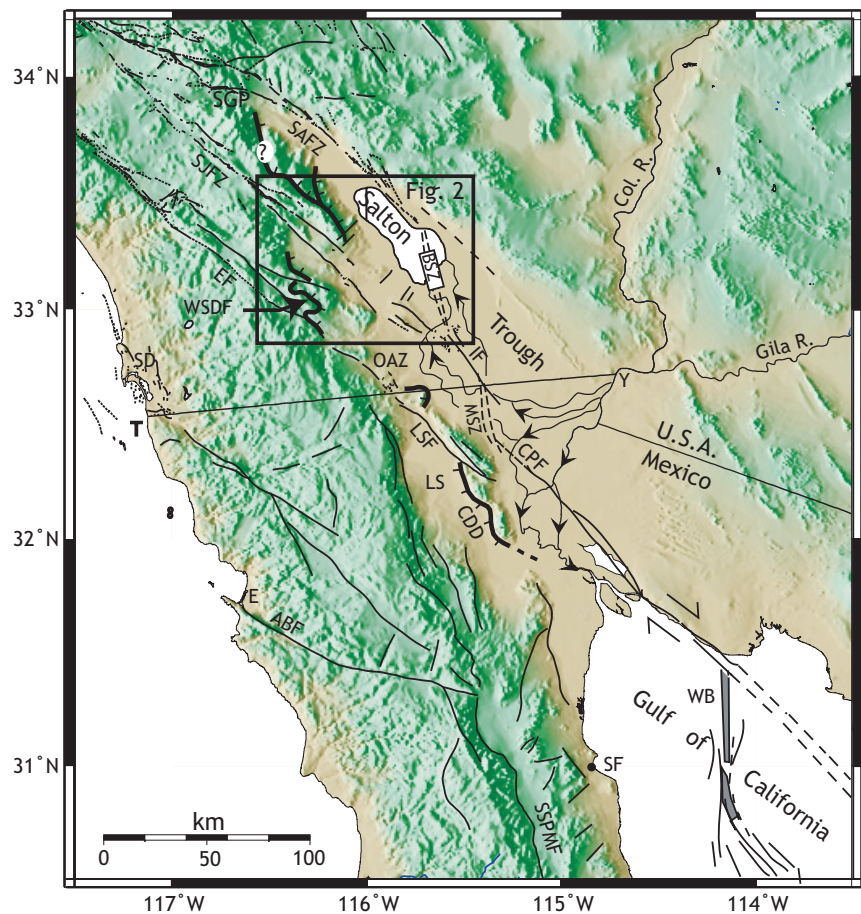


Figure 5.1
Faults and Topography of the Northern Gulf of California and Salton Trough Region.

Decorated thicker lines are detachment faults, tick marks on upper plate; plain lines are high-angle normal and strike-slip faults. Explanation: ABF, Agua Blanca fault; BSZ, Brawley Spreading zone; CDD, Cañada David detachment; CPF, Cerro Prieto fault; E, Ensenada; IF, Imperial fault; SAFZ, San Andreas fault zone; SD, San Diego; SGP, San Geronimo Pass; SF, San Felipe; SJFZ, San Jacinto fault zone; SSPMF, Sierra San Pedro Martir fault; T, Tijuana; and WB, Wagner basin. (Shaded-relief map base courtesy of H. Magistrale)

Prior Work

Our understanding of geological events summarized below is based on decades of research by many scientists. This chapter does not present new data, it is simply an attempt to synthesize a vast body of existing knowledge and make it accessible to a broad audience. Some of the more influential studies of regional stratigraphy, basin evolution, and related structures in the western Salton Trough appear in papers and theses by: Axen and Fletcher (1998), Bartholomew (1968, 1970), Brown et al. (1991), Dean (1988, 1996), Dibblee

(1954, 1984, 1996a, 1996b), Dronyk (1977), Feragen (1986), Frost et al. (1996a, 1996b), Girty and Armitage (1989), Ingle (1974), Johnson et al. (1983), Kerr (1982, 1984), Kerr and Kidwell (1991), Lough (1993, 1998), Merriam and Brady (1965), Muffler and Doe (1968), Opdyke et al. (1977), Quinn and Cronin (1984), Remeika (1995), Remeika and Beske-Diehl (1996), Schultejaann (1984), Sharp (1982), Stinson (1990), Stinson and Gastil (1996), Tarbet and Holman (1944), Wells (1987), Winker (1987), Winker and Kidwell (1986, 1996), Woodard (1963, 1974). This list is only a partial sampling of many theses, papers, and abstracts that have contributed to our understanding of this fascinating region. Interested readers are encouraged to explore the original literature upon which the following summary is based.

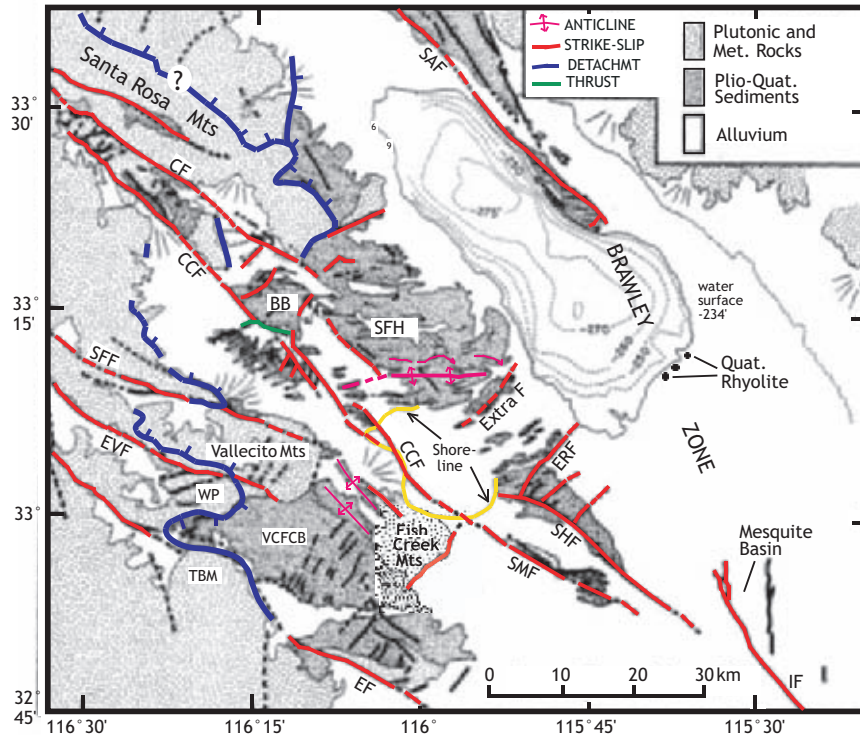


Figure 5.2
Geologic Map of the Salton Trough Region.

Explanation: BB, Borrego Badlands; CF, Clark fault; CCF, Coyote Creek fault; EF, Elsinore fault; ERF, Elmore Ranch fault; EVF, Earthquake Valley fault; VCFCB, Vallecito Creek-Fish Creek basin; IF, Imperial fault; SFF, San Felipe fault; SFH, San Felipe Hills; SHF, Superstition Hills fault; SMF, Superstition Mtn fault; TBM, Tierra Blanca Mts; and WP, Whale Peak. (Map compilation courtesy of L. Seeber)

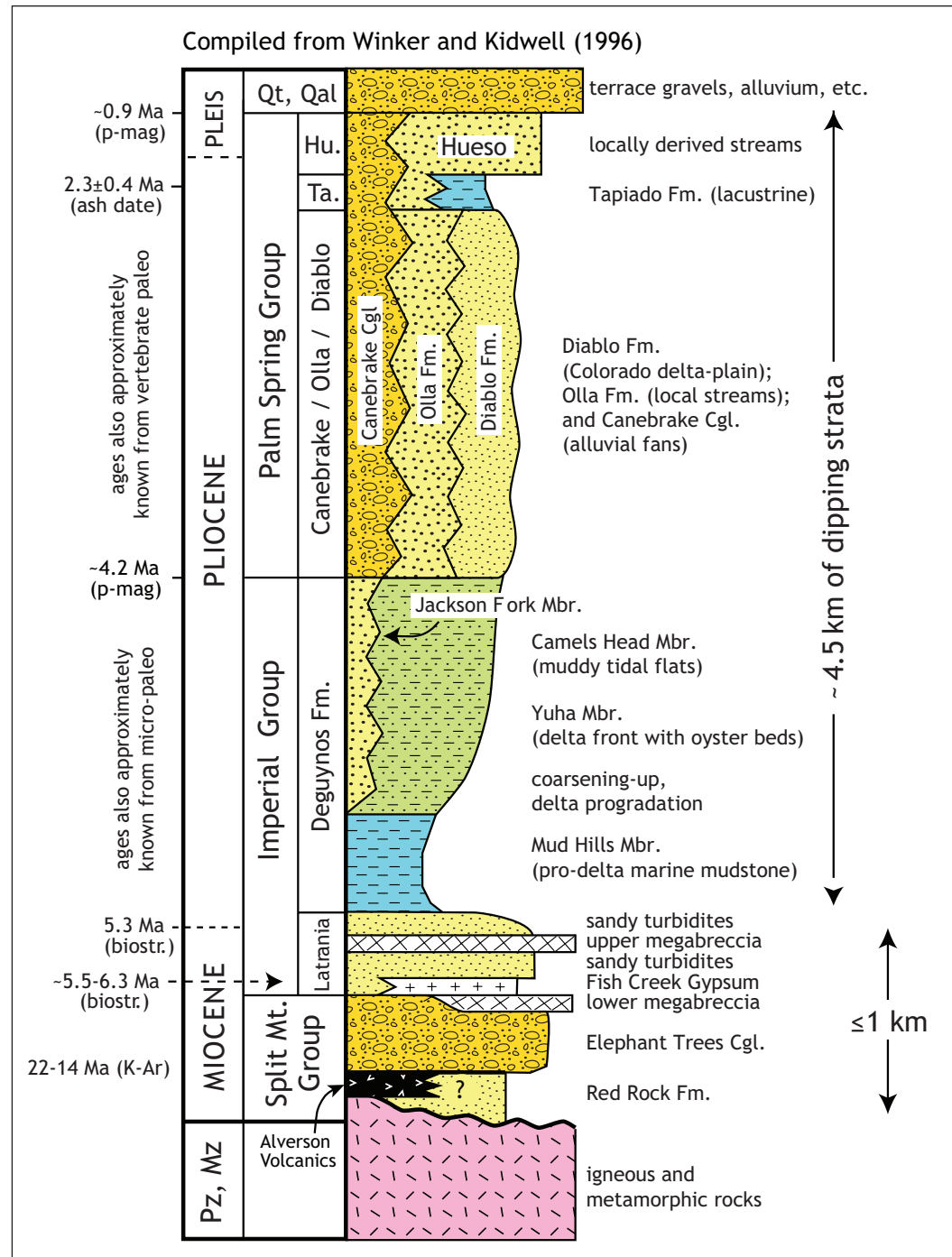


Figure 5.3

Generalized Stratigraphic Column for the Vallecito Creek-Fish Creek Stratigraphic Section.

Paleomagnetic and ash dates are from Opdyke et al. (1977) and Johnson et al. (1983). Biostratigraphic age controls are from studies of Stump (1972), Downs and White (1968), Ingle (1974), Pappajohn (1980), Dean (1988), and McDougall (personal communication, cited in Winker and Kidwell, 1996). K-Ar (potassium-argon) ages in the Alverson Volcanics are from Ruisaard (1979) and Gjerde (1982), summarized by Kerr (1982). Adapted from Winker and Kidwell (1996).

Tectonics, Stratigraphy, and Basin Evolution

Overview

Changing patterns of faulting and subsidence in the San Andreas system have exerted a primary control on sedimentation and stratigraphy in the western Salton Trough through time. Although significant uncertainties and questions remain, the Miocene to Pleistocene tectonic evolution of this region can generally be divided into three stages: (1) early (?) to late Miocene continental sedimentation, volcanism, and formation of fault-bounded nonmarine rift basins; (2) Pliocene to early Pleistocene extension and transtension on a system of regional detachment faults (low-angle normal faults) and formation of a large basin that filled first with marine and later with terrestrial sediments; and (3) Pleistocene

to modern strike-slip faulting and related folding in the San Jacinto and Elsinore fault zones, which results in uplift and erosion of the older deposits. Much of the evidence for these tectonic stages is contained in deposits that accumulated in ancient sedimentary basins. Thus, the stratigraphy can be regarded as both an integral component of the dynamic fault-basin system, and a natural record, not always easy to read, of the tectonic processes that produced them.

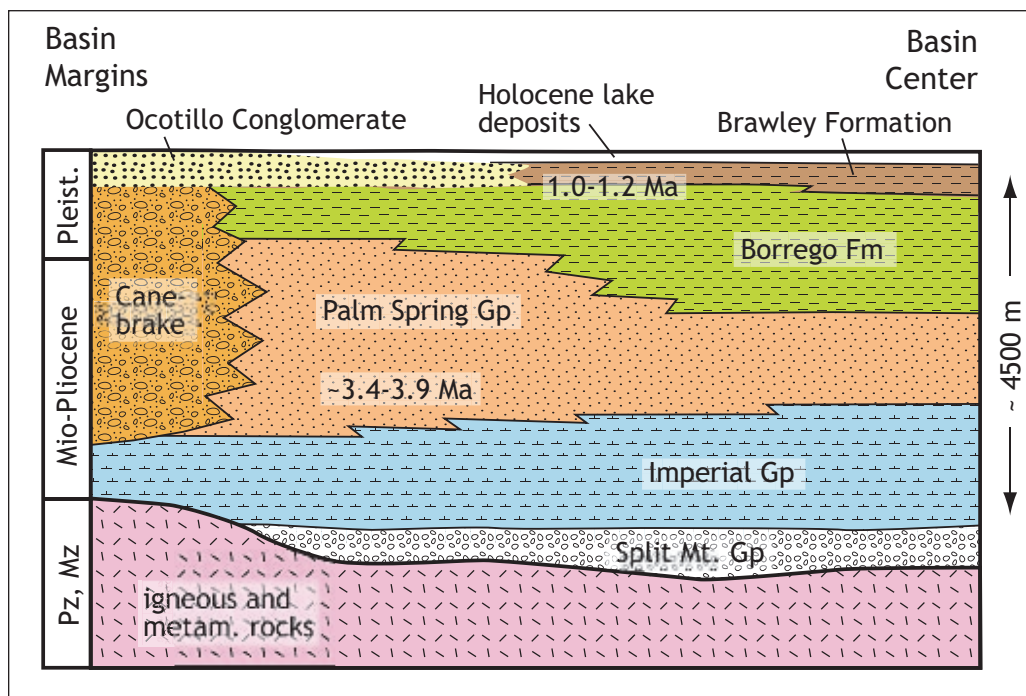


Figure 5.4
Stratigraphy of the Northwestern Salton Trough. Age of lower Palm Spring Group is based on micropaleontologic study of Quinn and Cronin (1984); age of the base of the Ocotillo Conglomerate is based on paleomagnetic studies by Brown et al. (1991) and Remeika and Beske-Diehl (1996). Modified from Abbott (1969), Dibblee (1954) and Sharp (1982).

The Neogene (Miocene to Pleistocene) stratigraphy of the western Salton Trough and Imperial Valley is illustrated in Figures 5.3 and 5.4. Ages of the deposits have been determined from studies of micropaleontology, vertebrate paleontology, geochronology, and paleomagnetism (see references in figure captions; see also related discussions in this volume: *Remeika Dating, Ashes and Magnetics, Cassiliano Mammalian Biostratigraphy in the Vallecito Creek and Fish Creek Basins, McDonald Anza-Borrego and the Great American Biotic Interchange*, and Sussman et al. *Paleoclimates and Environmental Change*). Figure 5.3 organizes the stratigraphy of the well-studied Vallecito Creek-Fish Creek area into subdivisions that reflect evolving ideas about the

architecture and organization of this complex succession of strata (e.g. Winker, 1987; Kerr and Kidwell, 1991; Winker and Kidwell, 1996). Appendix Table 4 “Correlation of Stratigraphic Names” provides an overview of stratigraphic nomenclature in the Vallecito Creek-Fish Creek section (the far right column is the convention used in this volume).

Neogene deposits in the northwestern Salton Trough (Figure 5.4) show similarities and differences with strata in the Vallecito Creek-Fish Creek section. Upper Miocene sedimentary rocks in the northwestern Trough are sporadically exposed around the margins of the basin and typically are thinner and less complete than in Split Mountain Gorge, though they are locally abundant in the southern Santa Rosa Mountains (Hoover, 1965; Cox et al., 2002; Matti et al., 2002). The Imperial and Palm Spring Groups in the San Felipe Hills are similar to the same units in the Vallecito Creek-Fish Creek stratigraphic section, but the lacustrine (lake) Borrego Formation is much thicker than the Tapiado Formation, and the Ocotillo Conglomerate is a widespread coarse alluvial unit in the northwestern Trough that has only a limited extent in the Vallecito Creek-Fish Creek area (Figures 5.3, 5.4; Dibblee, 1954, 1984, 1996a, 1996b; Bartholomew, 1968). These similarities and differences suggest that the two areas may have occupied a single integrated basin during deposition of the Mio-Pliocene Imperial and early Palm Spring Groups, but became segregated into separate sub-basins in late Pliocene time (Dorsey et al., 2004).

Axen and Fletcher (1998) showed that the Imperial and Palm Spring Groups, and possibly the upper part of the Split Mountain Group, accumulated in a large sedimentary basin that was bounded on its western margin by the west Salton detachment fault system (tectonic stage 2, above) from late Miocene to early Pleistocene time. Detachment faults are low-angle normal faults that form in areas of strong regional extension; they are sometimes associated with high crustal heat flow and commonly produce large sedimentary basins in their upper plates (Figure 5.5; e.g. Wernicke, 1985; Friedmann and Burbank, 1995; Miller and John, 1999). The west Salton detachment fault system was recognized in prior studies and was widely believed to be early or middle Miocene age (e.g. Stinson and Gastil, 1996; Frost et al., 1996a, 1996b). The synthesis by Axen and Fletcher (1998) presented evidence that slip on the detachment system probably began in late Miocene time and continued through Pliocene into early

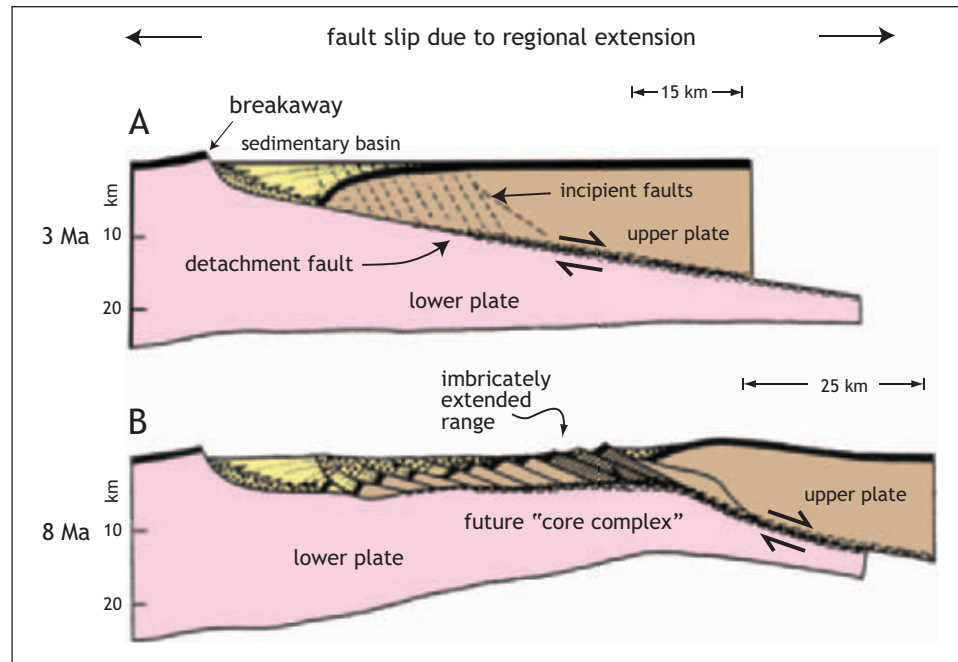


Figure 5.5
Conceptual Model for Partial Evolution of a Detachment Fault (low-angle normal fault) and Upper-plate (supradetachment) Sedimentary Basin Created by Regional Extension.

A. Early slip on the fault occurs by brittle shearing in the shallow crust and ductile deformation in the middle to lower crust. The curved, listric geometry of the breakaway produces a rollover monocline in the upper plate, which in turn produces a sedimentary basin that accumulates a thick section of syn-extensional deposits.

B. After about 8 million years of fault slip, the lower plate domes upward and the upper plate breaks apart along a series of closely spaced normal faults that disrupt sedimentation in the basin. Note that the upper plate of the west Salton detachment fault system *did not* experience break-up as shown in B, possibly because slip on the detachment was terminated by initiation of strike-slip faulting in late Pliocene or early Pleistocene time. Modified from Wernicke (1985).

Pleistocene time. Detachment faulting resulted in widespread crustal subsidence and accumulation of thick sedimentary deposits that are now exposed in the western Salton Trough (Figures 5.2, 5.3). In contrast to many well-known detachment fault systems, the upper-plate basin of the west Salton detachment fault was not significantly broken apart by normal faults, perhaps because slip on the detachment was terminated by initiation of strike-slip faulting (tectonic stage 3). Moreover, it experienced an oblique, partially strike-slip component of movement that is unlike orthogonal detachment faults (Steely et al., 2004a, 2004b; Axen et al., 2004). These and other aspects of faulting and basin evolution in the Salton Trough are the subject of ongoing study by the author and her colleagues.

The three stages of tectonic evolution and basin development are briefly summarized below. The events are described from earlier to later, moving from lower to higher in the stratigraphic column. Stage 1 (Miocene) is best recorded in rocks exposed in and around Split Mountain Gorge. Stage 2 (Pliocene to early Pleistocene) is recorded in widespread deposits of the Imperial and Palm Spring Groups that are exposed extensively around the western Salton Trough region (Figure 5.2). Geomorphic, structural, and geophysical evidence for stage 3 (Pleistocene to modern) is ubiquitous in the landscape and is reflected in present-day mountain ranges and ridges, active fault scarps, alluvial fans, eroding badlands, and playa lakes.

1. Early to Late Miocene

Significant accumulation of Neogene strata began with deposition of lower Miocene continental sandstone and conglomerate of the Red Rock Formation, which occupies the lower part of the Split Mountain Group (Kerr and Kidwell, 1991; Winker and Kidwell, 1996). These deposits accumulated in rivers and eolian (wind-borne) sand dunes that filled in rugged paleotopography formed by earlier erosion of granitic and metamorphic rocks of the Peninsular Ranges batholith. In some places, they are conformably overlain by volcanic basalts, breccias, and interbedded basalt-clast conglomerates of the middle Miocene Alverson volcanics, which have been dated at approximately 22 to 14 Ma (Figure 5.3; Gjerde, 1982; Ruisaard, 1979; Kerr, 1982). Based on relationships between faulted volcanic and sedimentary rocks, Winker and Kidwell (2002) inferred that weak regional extension and slip on high-angle normal faults began during emplacement of the Alverson volcanics, prior to the late Miocene phase of strong extension and rift-basin development.

The Split Mountain Formation of earlier workers (e.g. Woodard, 1974) includes conglomerate, breccia, and sandy marine turbidites exposed in Split Mountain Gorge. Based on the conformable transition to Imperial marine strata, the upper, marine part of the Split Mountain Formation was reassigned to the lower Imperial Formation (Kerr and Kidwell, 1991), and later named the Latrania Formation of the Imperial Group (Winker and Kidwell, 1996; Remeika, 1998). The Anza, Alverson, and lower Split Mountain Formations were assigned to the Split Mountain Group in this revision (Figure 5.3; Winker and Kidwell,

1996). In the Vallecito Creek-Fish Creek basin, sedimentologically variable marine deposits of the Latrania Formation are conformably overlain by regionally extensive fine-grained marine deposits of the Deguynos Formation (Winker and Kidwell, 1996; Remeika, 1998).

The stratigraphy of the Split Mountain and lower Imperial Groups is very complex, exhibiting abrupt lateral changes in facies (texture, sedimentary structures, grain size, and composition) and local thickening into the Split Mountain Gorge area (e.g. Winker, 1987). These units include two megabreccias with huge clasts (boulder to house-size rock fragments) that were emplaced catastrophically by large rock avalanches, or “sturzsstroms” (Figure 5.3; Kerr and Abbott, 1996; Rightmer and Abbott, 1996; Shaller and Shaller, 1996). The Elephant Trees Conglomerate (formerly Split Mountain Formation) is an impressive unit of coarse-grained debris flow and sheet flood deposits that are superbly exposed in the walls of Split Mountain Gorge (Figure 5.6). The age of the Elephant Trees is uncertain (e.g. Kerr and Kidwell, 1991; Winker and Kidwell, 1996). Pronounced lateral thickening of the conglomerate, its conformable association with sandstone of the underlying Red Rock Formation, and the presence of normal faults overlapped by sedimentary deposits, provide evidence that this area experienced sedimentation in steep alluvial fans and flanking braided streams in an active rift basin during late Miocene extension on high-angle normal faults (Kerr, 1982, 1984; Winker, 1987; Winker and Kidwell, 1996).

The Fish Creek Gypsum is a thick, discontinuous deposit that occupies the transition from nonmarine deposits of the Split Mountain Group to marine turbidites of the lower Imperial Group (Figure 5.3; Dean, 1988; 1996; Winker and Kidwell, 1996). Neither its age nor its origins are agreed upon by geologists at this time. Index species (taxa exclusively associated with a particular time interval) of calcareous nanoplankton indicate an age of 3.4-6.3 Ma (million years) for the gypsum (Dean, 1996). This age is refined by tentative placement of the Miocene-Pliocene boundary (5.3 Ma) in the overlying Latrania Formation by Winker and Kidwell (1996), suggesting that its age is approximately 6.3 to 5.5 Ma. The environment of formation for the Fish Creek Gypsum has been variably interpreted as a marginal-marine evaporite setting (Winker, 1987), a restricted shallow-marine basin (Dean, 1988; 1996), or a marine basin with precipitation of gypsum from a hydrothermal vent system (Jefferson and Peterson,



Figure 5.6
Split Mountain Group.
Elephant Trees Conglomerate of the Split Mountain Group in Split Mountain Gorge, showing interbedded sandstone and boulder conglomerate that formed in an alluvial fan setting. (Photograph by Rebecca Dorsey)

1998). These diverse interpretations highlight the existing uncertainty about the origin of the gypsum and its relation to tectonic evolution at Split Mountain Gorge.

The Fish Creek Gypsum and laterally equivalent lower Latrania Formation record a rapid transgression of marine waters that apparently was controlled by a change in the regional tectonic regime. Onset of late Miocene rifting and high-angle normal faulting recorded in the Split Mountain Group may have been related to early movement on the west Salton detachment fault system (Axen and Fletcher, 1998), or it may represent a distinct earlier phase of extension that pre-dates detachment faulting (Dorsey and Janecke, 2002; Winker and Kidwell, 2002). In either interpretation, it appears that a major tectonic change at about 6-7 Ma produced nearly synchronous marine incursion throughout the northern Gulf of California and Salton Trough region. This incursion flooded an area at least 400 km (250 miles) long, from San Felipe, Mexico, in the south, to San Gorgonio Pass in the north (Figure 5.1; Oskin and Stock, 2003) (see also Deméré, this volume, *The Imperial Sea*).

Recent studies on Isla Tiburon, Mexico, have shown that marine deposits there are younger than about 6.2 Ma, contrary to previous interpretations, and that tectonic opening of the northern Gulf of California was initiated when dextral (right lateral strike-slip) plate motion stepped into the Gulf at about 6.0-6.2 Ma (Gastil et al., 1999; Oskin et al., 2001; Oskin and Stock, 2003). Oskin and Stock (2003) noted that the age of the oldest marine deposits is remarkably similar throughout the northern Gulf and Salton Trough region. Micropaleontology of diatomite near San Felipe indicates that the oldest marine deposits there accumulated between about 5.5 and 6.0 Ma (Boehm, 1984). At San Gorgonio Pass, the Imperial Group is about 6.5 to 6.3 Ma based on micropaleontologic and geochronologic data (McDougall et al., 1999; and papers cited therein). An age of about 6.3 to 5.5 Ma for the Fish Creek Gypsum in the Split Mt. area (Dean, 1988, 1996) is consistent with the timing of marine incursion in other locations around the northern Gulf and Salton Trough region. Rapid marine flooding during this short time interval probably resulted from accelerated basin subsidence and crustal thinning related to initiation of the active plate boundary in the Salton Trough at about 6 Ma (Oskin and Stock, 2003). In addition, a rapid rise in global sea level in latest Miocene time (e.g. Haq et al., 1987) may have caused flooding of an area even larger than would have resulted from tectonic forces alone.

2. *Pliocene to Early Pleistocene*

The Pliocene was a time of deep basin subsidence and accumulation of thick marine and nonmarine sedimentary rocks of the Imperial and Palm Spring Groups throughout the western Salton Trough region (Figures 5.2, 5.3, 5.4). Widespread, fine-grained marine deposits of the Deguynos Formation rest on coarse-grained facies of the Split Mountain Group and Latrania Formation, and represent the culmination of the latest Miocene marine incursion (e.g. Winker

and Kidwell, 1996). The tectonic setting was dominated by slip on the west Salton detachment fault system, whose bedrock and basin remains are exposed today around the western fringes of the Salton Trough (Figures 5.2, 5.3; Axen and Fletcher, 1998). The Miocene-Pliocene boundary at Split Mountain has tentatively been placed in the upper part of the Latrania Formation, above the upper megabreccia and at the base of the oldest recorded Colorado River-derived sandstones (Figure 5.3; K. McDougall, personal communication, as cited in Winker and Kidwell, 1996; Gastil et al., 1996). This stratigraphic transition is generally not exposed in the northwestern Salton Trough, but was penetrated by deep exploratory wells in the San Felipe Hills (Dibblee, 1984). The change from locally variable, coarse-grained Latrania deposits of upper Miocene age to regionally extensive fine-grained marine deposits of the lower Pliocene Deguynos Formation may be related to rapid subsidence rates (~ 5 mm/yr [1/5 in.]; Johnson et al., 1983) that overwhelmed the sediment supply and submerged the Salton Trough basin during early Pliocene time. This period of rapid subsidence probably was driven by the same tectonic forces that produced the latest Miocene marine incursion: initiation or acceleration of relative plate motion in the northern Gulf-Salton Trough region and initiation or integration of the detachment fault system.

Through a combination of tectonic controls, the Salton Trough and northern Gulf of California became a large elongate seaway in early Pliocene time that accumulated a thick succession of marine fossiliferous claystone, siltstone, sandstone, and minor limestones of the Imperial Group (Figures 5.3, 5.4, 5.7). During this time, southern California was located about 200 km (125 miles) southeast of its present location relative to North America, and the Salton Trough was part of a long marine embayment that

extended a large distance to the north (Figure 5.9A; Winker, 1987; Winker and Kidwell, 1986). Shortly after the marine transgression that produced the Imperial seaway, this region became the site of a distal prodelta (outermost delta) where only very fine-grained clay and silt derived from the ancestral Colorado River were deposited by suspension settling from the marine water column. This is recorded in mudstone and silty rhythmite of the Deguynos Formation (Figure 5.3; Winker and Kidwell, 1996; 2002) and by similar deposits of the Imperial Group in the San Felipe Hills (Figure 5.4; Dibblee, 1954, 1984; Quinn and Cronin, 1984). Later, as the Pacific plate moved northwest relative to North America, fine-grained sand from the ancestral Colorado



Figure 5.7
Upper Imperial Group.
Tan fine-grained marine mudstone capped by oyster beds in the upper Imperial Group, Vallecito Creek-Fish Creek basin; white patch in distance is Fish Creek Gypsum in the western Fish Creek Mts. (Photograph by Rebecca Dorsey)

River advanced into the basin via dilute turbidity currents. This produced a coarsening-up trend in sediments of the upper Imperial Group that reflects gradual shallowing of the basin as it filled with Colorado River-derived sediments (Figures 5.3, 5.4). The youngest deposits of the Imperial Group include fossiliferous claystone disturbed by burrowing marine animals, wavy-bedded sandstone, and foraminifers (shelled protozoans) that indicate intertidal brackish water conditions; this suggests deposition in a low-energy intertidal environment similar to the broad modern tidal flats that occupy a large area of the present-day lower Colorado delta at the north end of the Gulf of California (Figure 5.1; Woodard, 1974; Quinn and Cronin, 1984; Winker, 1987; Winker and Kidwell, 1996). Marine deposits of the Imperial Group can be viewed along the sides of Fish Creek Wash, south of Split Mountain Gorge.

Shallow marine units of the upper Imperial Group are gradationally overlain by the Arroyo Diablo Formation, a thick unit of sandstone and mudstone that is exposed over much of the Salton Trough region (Figures 5.2, 5.3, 5.4). Quartzose sand of the Arroyo Diablo and Olla Formations (Figure 5.8) was eroded from the Colorado Plateau and deposited in the ancestral Colorado River delta which, at about 3.0 Ma, was located approximately 60-70 km (40 miles) southwest of the modern point of entry of the Colorado River into the Salton



Figure 5.8
Lower Palm Spring Group.
Channelized sandstone (tan color) and red mudstone of the Olla Formation (Palm Spring Group) that was deposited in the ancestral Colorado River delta plain. (Photograph by Rebecca Dorsey)

Trough (Figure 5.9B; Girty and Armitage, 1989; Guthrie, 1990; Winker and Kidwell, 1986). Deposition took place in a subaerial delta-plain setting that was characterized by laterally shifting distributary channels and interchannel swamps and marshes, with overall transport toward the southeast (Winker and Kidwell, 1986). The presence of fossil wood varieties including walnut, ash, and cottonwood suggests that the Pliocene climate was wetter and cooler than today (Remeika et al., 1988; Remeika and Fleming, 1995; see Remeika, this volume, *Ancestral Woodlands of the Colorado River Delta Plain*). The Canebrake Conglomerate, a coarse-grained lateral equivalent of the Arroyo Diablo Formation and other younger units, accumulated in alluvial fans and braided streams on the flanks of steep mountains around the margins of the delta plain (e.g. Dibblee, 1954, 1984; Hoover, 1965; Winker, 1987).

The base of the lacustrine (lake) Tapiado and fluvial Hueso Formations (Figure 5.3) marks an abrupt end of Colorado river input in the Fish Creek area (Winker, 1987; Winker and Kidwell, 1986, 1996). This transition coincides

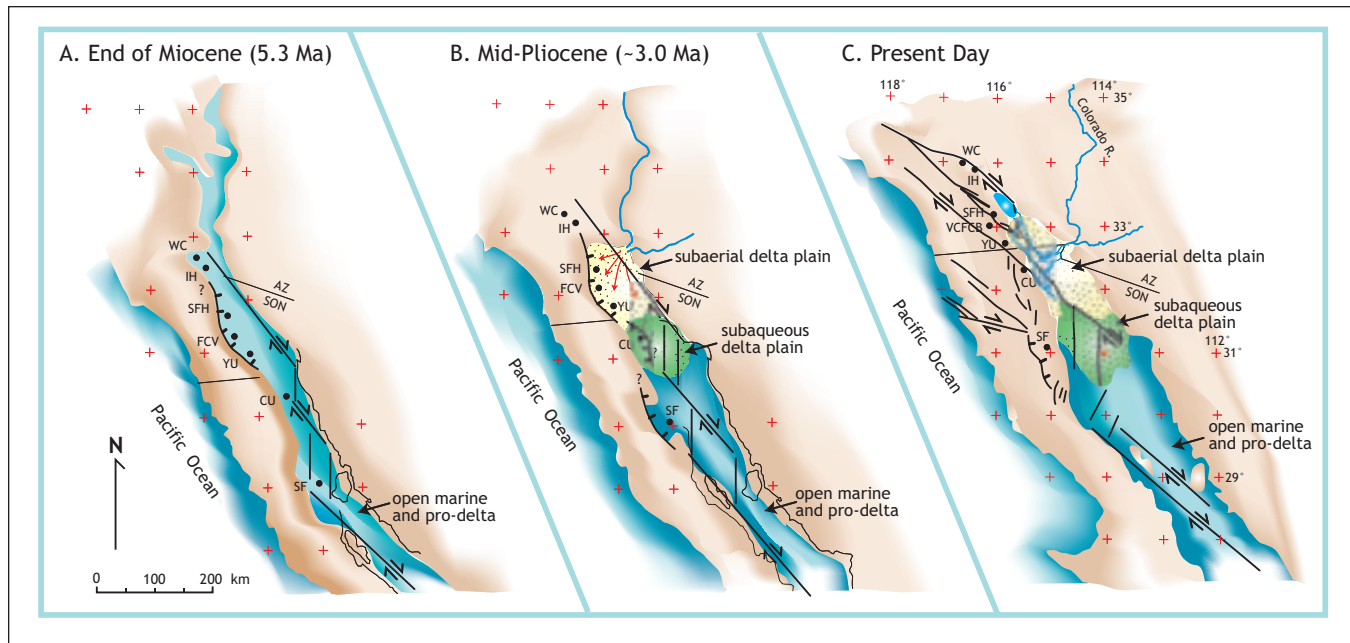


Figure 5.9
Paleogeographic Reconstructions of Sedimentary Basins and Faults in the Salton Trough and Northern Gulf of California Since the End of Miocene Time.

Southern California and northern Baja California have been moving to the northwest relative to stable North America since localization of the plate boundary in the Gulf of California at ~6.5-6.0 Ma (Oskin and Stock, 2003) or possibly earlier.

A. End of Miocene time, shortly after widespread marine incursion in the Salton Trough and northern Gulf of California.

B. Deposition of Palm Spring Group in the ancestral Colorado River delta.

C. Present-day geography, active faults, and environments. Explanation: CU, Sierra Cucapas; VCFCB, Vallecito Creek-Fish Creek basin; IH, Indio Hills; SF, San Felipe; SFH, San Felipe Hills; and WC, Whitewater Canyon. Thick lines with arrows are strike-slip faults showing relative movement; thick lines with tic marks are normal faults (low-angle detachment faults in A and B). Red arrows in B indicate inferred sediment transport directions (based on Winker and Kidwell, 1986) (see text for explanation). Redrafted from Winker (1987) with modifications from Axen (1995), Axen and Fletcher (1998), and Oskin et al. (2001).

approximately with the end of stratigraphic similarities between sediments in the Fish Creek area and the northwestern Salton Trough, and may have resulted from reorganization of the basin (Figures 5.3, 5.4; Dorsey et al., 2004). The Borrego Formation is a very thick succession of lake deposits exposed in the Borrego Badlands and San Felipe Hills that may be partially equivalent to the Tapiado Formation, but its age and stratigraphic architecture are not well known. The Borrego Formation contains abundant claystone and siltstone and rare sandstone beds with both Colorado River- and locally-derived sandstones. Our knowledge of the Borrego Formation and its paleontology, paleogeography, and Pliocene evolution in the northwestern Salton Trough is based largely on previous studies by Tarbet and Holman (1944), Morley (1963), Dibblee (1954, 1984), Hoover (1965), Merriam and Bandy (1965), Bartholomew (1968); Dronyk (1977), Feragen (1986), Wells (1987), as well as recent studies by Kirby et al., (2004a, 2004b), Steely et al. (2004a, 2004b), and Dorsey et al. (2004). Ostracodes (small crustaceans, mussel shrimp) and benthic foraminifers reflect deposition in fresh water to brackish and alkaline conditions (see Appendix, Table 2). The Borrego Formation represents a large perennial lake basin that became isolated from the

Gulf of California as it moved tectonically to the northwest past the Colorado River delta into its present position (Figure 5.1; Kirby et al., 2004a, 2004b, Dorsey et al., 2004).

The youngest deposits of the Palm Spring Group are early Pleistocene, locally derived sandstone and conglomerate of the Hueso Formation in the Vallecito Creek-Fish Creek area (Figure 5.3; Winker and Kidwell, 1996; Cassiliano, 2002) and Ocotillo Conglomerate in the Borrego and Ocotillo Badlands (Figure 5.4; Dibblee, 1954; 1984; Brown et al., 1991; Bartholomew, 1968, 1970; Lutz, 2005). These deposits accumulated in alluvial fans and ephemeral streams that drained nearby fault-bounded mountain ranges. Deposition took place in sedimentary basins that were shaped by slip on early strands of the San Jacinto fault zone (Bartholomew, 1970; Pettinga, 1991; Lutz and Dorsey, 2003; Kirby et al., 2004a, 2004b; Kirby, 2005; Lutz, 2005). The Hueso Formation is exposed in View of the Badlands Wash (Vallecito Creek-Fish Creek Badlands), and the Ocotillo Conglomerate can be seen in the cliffs directly beneath Fonts Point in the Borrego Badlands.

3. *Early Pleistocene to Present*

Initiation of the San Jacinto and Elsinore fault zones marks the onset of complex dextral strike-slip faulting and north-south compression in the western Salton Trough, which continues today (Figure 5.10, 5.9C). Knowledge of this stage is based on studies by Sharp (1967), Wesnousky (1986), Hudnut and Sieh (1989), Hudnut et al. (1989), Rockwell et al. (1990), Brown

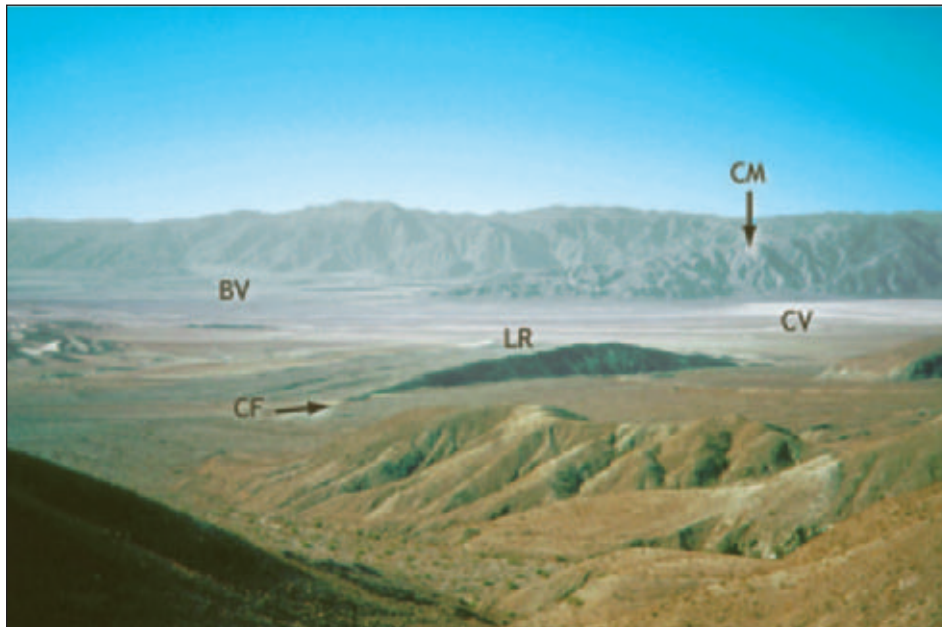


Figure 5.10
Geomorphology Along the San Jacinto Fault Zone.
View looking west across Coyote Mountain (CM), Clark Valley (CV), Borrego Valley (BV), and Lute Ridge (LR). Lute Ridge is a deposit of Pleistocene coarse alluvial gravels that have been displaced and translated by right-lateral slip on the Clark fault (CF). (Photograph by Rebecca Dorsey)

et al. (1991), Petersen et al. (1991), Sanders and Magistrale (1997), Heitmann (2002), Dorsey (2002), Ryter (2002), Janecke et al. (2003, 2004), Kirby et al. (2004a, 2004b), Lutz and Dorsey (2003), Lutz et al. (2004), Lutz (2005), and others. In spite of its young age, the timing and nature of the transition from transtensional detachment faulting to transpressive strike-slip faulting is poorly understood. Strike-slip faulting may have overlapped in time with movement on the detachment fault system, and the San Jacinto and Elsinore faults could have started at similar or different times. Dorsey (2002) suggested that progradation (spreading into the basin and over the top of the Borrego Formation lacustrine deposits) of the Ocotillo Conglomerate in the Borrego Badlands may have resulted from initiation of the San Jacinto fault at approximately 1.5 Ma, a date consistent with some prior estimates (e.g. Bartholomew, 1970; Morton and

Matti, 1993). Other studies have inferred an earlier, Pliocene age for the San Jacinto fault zone based on total fault offset and late Pleistocene slip rates (e.g. Rockwell et al., 1990). The Fonts Point Sandstone is a thin Pleistocene fluvial deposit with a well developed calcic paleosol (carbonate cemented ancient soil) layer. This paleosol records the end of sediment accumulation in the Borrego Badlands during slip on the Coyote Creek fault (Ryter, 2002; Lutz et al., 2004; Lutz, 2005). Based on the age of deformed sediments in the Vallecito Creek area (Johnson et al., 1983), Ocotillo Badlands (Brown et al., 1991), San Felipe Hills (Kirby et al., 2004a, 2004b), and Borrego Badlands (Remeika and Beske-Diehl, 1996; Lutz, 2005), combined with known structural relationships in the region (e.g. Dibblee, 1984; Brown et al., 1991; Janecke et al., 2003, 2004; Kirby, 2005), it is likely that the San Jacinto and Elsinore fault systems were initiated in late Pliocene or early Pleistocene time.

Early to middle Pleistocene age conglomerate, sandstone and mudstone, exposed along the northwestern San Jacinto fault zone, was informally named “Bautista beds” by Frick (1921) and later mapped and studied by Sharp (1967) and Dorsey (2002). Sharp (1967) expanded the name “Bautista beds” to include Pleistocene sedimentary rocks exposed around Clark Lake and the northern Borrego Badlands, but these deposits had already been named “Ocotillo Conglomerate” by Dibblee (1954). Recent study by Dorsey and Roering (in press) shows that the Bautista beds were deposited by west- to northwest-flowing streams on the high west flank of the Peninsular Ranges during an early phase of slip in the San Jacinto fault zone. These low-gradient streams were later captured by headward erosion in steep streams flowing southeast along the modern fault zone. The Ocotillo Conglomerate in the Borrego Badlands (“Ocotillo Formation” of Remeika and Beske-Dehl, 1998; Lutz, 2005) was deposited in a low-lying basin (depocenter) at the western margin of the Salton Trough, in a physiographic setting quite different than that of the Bautista beds.

The modern phase of active faulting and seismicity has created a rugged landscape characterized by northwest-trending ridges and fault-controlled features such as Coyote Mountain, Clark Valley, and Lute Ridge (Figure 5.10). Active faults and related uplift have produced young landforms in areas such as the Borrego Badlands, Superstition Mountain, and Superstition Hills, causing older basin deposits to be eroded and reworked into young terrace deposits and modern washes (e.g. Dibblee, 1954, 1984; Ryter, 2002). The Salton Sea is a large topographic depression that exists because of ongoing oblique extension and subsidence within a releasing step-over between the Imperial and San Andreas faults, which has produced an oblique spreading center (the Brawley seismic zone) (Figure 5.1; Elders et al., 1972; Fuis et al., 1982; Fuis and Kohler, 1984; Elders and Sass, 1988). This region has repeatedly dried out and filled with waters of ancient Lake Cahuilla, a Pleistocene to Holocene lake that previously lapped against the flanks of the San Felipe Hills and Santa Rosa Mountains (Waters, 1983). These lake-level highstands created distinctive calcareous algae-derived tufa deposits that are encrusted on granitic bedrock northwest of Salton City and in the Fish Creek Mountains along the U.S.

Gypsum mine railroad. Lake Cahuilla represents the most recent expression of a large ephemeral lake system that was repeatedly flooded and dried out during deposition of the Pleistocene Brawley Formation (Kirby et al., 2004a, 2004b; Kirby, 2005), but with a more restricted distribution that reflects active faulting controls on the modern depocenter.

Conclusions

The above summary provides a brief overview of the tectonic, basinal, and sedimentary history of the western Salton Trough region. We have seen that Anza-Borrego Desert State Park lies within an active plate-boundary zone – the San Andreas fault system – which has been absorbing relative movement of the Pacific and North American plates since about 30 Ma. During Pliocene to early Pleistocene time, a large sedimentary basin associated with slip on a regional detachment fault system accumulated a thick section of marine and nonmarine sediments, recording a wide range of environments that supported the evolution and preservation of ancient plants and animals. Climate also appears to have changed during this time, shifting from a wetter and cooler climate in late Miocene time to the hyper-arid desert setting of today. The modern phase of strike-slip faulting has resulted in uplift and erosion of older sediments, creating a rich natural archive ideal for studying ancient life forms and the environments in which they lived.

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