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

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

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 that defines the tectonically active boundary between the North American plate and the Pacific plate in southern California (Figs. 1, 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, 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), 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 (Figs. 2, 3, 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.

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), Schultejann (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.

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 – 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 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.

The Neogene (Miocene to Pleistocene) stratigraphy of the western Salton Trough and Imperial Valley is illustrated in Figures 3 and 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 following in this volume: Remeika "Ashes and Magnetics," Cassiliano "Mammalian Biostratigraphy," MacDonald "The Great American Biotic Interchange," and Sussman "Paleoclimates and Environmental Change." Figure 3 organizes the stratigraphy of the well-studied Fish Creek – Vallecito 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 1: "Stratigraphic Names Chart" 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 (Fig. 4) show similarities and differences with strata in the Fish Creek – Vallecito 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; Matte et al., 2002). The Imperial and Palm Spring Groups in the San Felipe Hills are similar to the same units in the Fish Creek – Vallecito Creek 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 Fish Creek – Vallecito Creek area (Figs. 3, 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 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 (Fig. 5; e.g. Warnock, 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 Pleistocene time. Detachment faulting resulted in widespread crustal subsidence and accumulation of thick sedimentary deposits that are now exposed in the western Salton Trough (Figs. 2, 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 (Fig. 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 (Fig. 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 (Fig. 3; Winker and Kidwell, 1996). In the Fish Creek – Vallecito 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 "sturzstroms" (Fig. 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 (Fig. 6A). 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 (Fig. 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); but tentative placement of the Miocene-Pliocene boundary (5.3 Ma) in the overlying Latrania Formation by Winker and Kidwell (1996) suggests 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, 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 (Fig. 1; Oskin and Stock, 2003) (See also Deméré, "The Imperial Sea," this volume.)

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 Formation 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 (Fig. 2, 3, 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 (Fig. 2, 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 (Fig. 3; K. McDougall, pers. 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 some 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 (Figs. 3, 4, 6B). 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 (Fig. 7A; Winker, 1987; Winker and Kidwell, 1986). Shortly after the marine transgression that produced the Imperial seaway, this region was 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 rhythmites of the Deguynos Formation (Fig. 3; Winker and Kidwell, 1996; 2003) and by similar deposits of the Imperial Formation in the San Felipe Hills (Fig. 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 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 (Figs. 3, 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 (Fig. 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 (Figs. 2, 3, 4). Quartzose sand of the Arroyo Diablo and Olla Formations (Fig. 6C) 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 Trough (Fig. 7B; 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 "Plants and Woods" in this volume). 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 (Fig. 3) marks an abrupt end of Colorado river input in the Fish Creek area (Winker, 1987; Winker and Kidwell, 1986, 1996). This transition coincides approximately with the end of stratigraphic similarities between sediments in the Fish Creek area and the northwestern Salton Trough, and may have resulted from structural segmentation of the basin (Figs. 3, 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 sandstone compositions. 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 Invertebrates). 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 (Fig. 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 Fish Creek – Vallecito Creek area (Fig. 3; Winker and Kidwell, 1996; Cassiliano, 2002) and Ocotillo Conglomerate in the Borrego and Ocotillo Badlands (Fig. 4; Dibblee, 1954; 1984; Brown et al., 1991; Bartholomew, 1968, 1970). 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). The Hueso Formation is exposed in View of the Badlands Wash (Vallecito 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 (Fig. 6D, 7C). 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 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), 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 faults may have overlapped in time with movement on the detachment fault system, and the San Jacinto and Elsinore faults could have initiated at similar or different times. Dorsey (2002) suggested that progradation of the Ocotillo Conglomerate in the Borrego Badlands may have resulted from initiation of the San Jacinto fault at approximately 1.5 Ma, 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 horizon) that records the end of sediment accumulation in the Borrego Badlands during slip on the Coyote Creek fault (Ryter, 2002; Lutz et al., 2004). 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 et al., 2004), combined with known structural relationships in the region (e.g. Dibblee, 1984; Brown et al., 1991; Janecke et al., 2003, 2004), it is likely that the San Jacinto and Elsinore fault systems were initiated in late Pliocene or early Pleistocene time.

A unit of early to middle Pleistocene 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 (submitted) 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 Lutz and Dorsey, 2003) was deposited in a low-lying 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 (Fig. 6D). Active faults and related uplift have produced young landforms in areas such as the Borrego Badlands, Superstition Mt., 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 in the Brawley seismic zone (Fig. 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 have 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 Gypsum 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), 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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References Cited

Abbott, W.O., 1969, Salton Basin, a model for Pacific rim diastrophism. Geological Society of America Special Paper 121, p.1.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. Geological Society of America Bulletin, v. 81, p. 3513-3536.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States - An update. International Geology Review, v. 40, p. 375-402.

Axen, G. J., 1995, Extensional segmentation of the main Gulf escarpment, Mexico and United States. Geology, v. 23, p. 515-518.

Axen, G. J., and Fletcher, J. M., 1998, Late Miocene-Pleistocene extensional faulting, northern Gulf of California, Mexico and Salton Trough, California. International Geology Review, v. 40, p. 217-244.

Bartholomew, M.J., 1968, Geology of the northern portion of Seventeen Palms and Font's Point quadrangles, Imperial and San Diego Counties, California. Master of Science Thesis, University of Southern California, Los Angeles, 60 p.

Bartholomew, M.J., 1970, San Jacinto Fault Zone in the northern Imperial Valley. Geological Society of America Bulletin, v. 81, p. 3161-3166.

Brown, N.N., M.D. Fuller, and R.H. Sibson, 1991, Paleomagnetism of the Ocotillo Badlands, southern California, and implications for slip transfer through an antidilational fault jog. Earth and Planetary Science Letters, v. 102, p. 277-288.

Cox, B. F., Matti, J. C., King, T., and Morton, D.M., 2002, Neogene strata of southern Santa Rosa Mountains, California, and their significance for tectonic evolution of western Salton Trough. Geological Society of America Abstracts with Programs. v. 34, no. 6, p.124.

Dean, M.A., 1988, Genesis, mineralogy, and stratigraphy of the Neogene Fish Creek Gypsum, southwestern Salton Trough, California. Unpubl. M.S. Thesis, San Diego State University, CA, 150 p.

Dean, M. A., 1996, Neogene Fish Creek Gypsum and associated stratigraphy and paleontology, southwestern Salton Trough, California. In Abbott, P. L., and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California. Santa Ana, California, South Coast Geological Society, p. 123-148.

DeMets, C., 1995, A reappraisal of seafloor spreading lineations in the Gulf of California: Implications for the transfer of Baja California to the Pacific plate and estimates of Pacific-North America motion. Geophysical Research Letters, v. 22, p. 3545-3548.

Dibblee, T. W., Jr., 1954, Geology of the Imperial Valley region, California. Geology of Southern California, California Division of Mines Bulletin 170, p. 21-28.

Dibblee, T.W., 1984, Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills, and vicinity. In Rigsby, C. A. (ed.), The Imperial Basin - Tectonics, Sedimentation, and Thermal Aspects. Los Angeles, California, Pacific Section S.E.P.M., p. 31-44.

Dibblee, T. W., Jr., 1996a, Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills and vicinity. In Abbott, P. L., and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park California. South Coast Geological Society Annual Field Trip Guide Book Number 24, p. 45-58.

Dibblee, T. W., Jr., 1996b, Stratigraphy and tectonics of the Vallecito-Fish Creek Mountains, Vallecito Badlands, Coyote Mountains, and Yuha Desert, southwestern Imperial Basin. In Abbott, P. L., and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park California. South Coast Geological Society Annual Field Trip Guide Book Number 24, p. 59-80.

Dickinson, W.R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system. Geological Society of America Special Paper 305, 46 p.

Dorsey, R.J., 2002, Stratigraphic record of Pleistocene initiation and slip on the Coyote Creek fault, lower Coyote Creek, southern California. In Barth, A. (ed.), Contributions to Crustal Evolution of the Southwest United States: Boulder, Co. GSA Special Paper 365, p. 251-269.

Dorsey, R.J. and Janecke, S.U., 2002, Late Miocene to Pleistocene West Salton Detachment Fault System and Basin Evolution, Southern California: New Insights. Geological Society of America Abstracts with Programs, v. 34, No. 6, p. 248.

Dorsey, R.J., Janecke, S.U., Kirby, S.M., Axen, G.J., and Steely, A.N., 2004, Pliocene lacustrine trangression in the western Salton trough, southern California: Implications for regional tectonics and evolution of the Colorado River delta. Geological Society of America Abstracts with Programs, v. 36, No. 5, p. 317-318.

Dorsey, R.J., and Roering, J.J., in press, Quaternary landscape evolution in the San Jacinto fault zone, Peninsular Ranges of southern California: Transient response to strike-slip fault initiation. *Geomorphology,* 2005.

Downs, T., and White, J.A., 1968, A vertebrate faunal succession in superposed sediments from late Pliocene to middle Pleistocene in California. In Tertiary/Quaternary Boundary, International Geological Congress 23, Prague v. 10, p. 41-47.

Dronyk, M.P., 1977, Stratigraphy, structure and seismic refraction survey of a portion of the San Felipe Hills, Imperial Valley, California. Master of Science Thesis, Department of Geological Sciences, University of California, Riverside 141 p.

Elders, W. A., Rex, R. W., Meidav, T., Robinson, P. T., and Biehler, S., 1972, Crustal Spreading in Southern California. Science v. 178, p. 15-24.

Elders, W. A., and Sass, J. H., 1988, The Salton Sea scientific drilling project. Journal of Geophysical Research, v. 93, p. 12,953-12,968.

Engel, A.E.J., and Schultejann, P.A., l984, Late Mesozoic and Cenozoic tectonic history of south central California. Tectonics v. 3, p. 659-675.

Feragen, E.S., 1986, Geology of the southeastern San Felipe Hills, Imperial Valley, California. [M.S. Thesis], San Diego State University, San Diego California, 144 p.

Frick, C., 1921, Extinct vertebrate faunas of the Badlands of Bautista Creek and San Timoteo Canyon, southern California: California University, Department of Geology Bulletin, v. 12, p. 277-424.

Friedmann, S.J., and Burbank, D.W., 1995, Rift basins and supradetachment basins: Intracontinental extensional end-members. Basin Research, v. **7**, p. 109-127.

Frost, E.G., Suitt, S.C., and Fattahipour, M.J., 1996a, Emerging perspectives of the Salton Trough region with an emphasis on extensional faulting and its implications for later San Andreas deformation. In Abbott, P. L., and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park California. South Coast Geological Society Annual Field Trip Guide Book Number 24, p. 81-122.

Frost, E.G., Fattahipour, M.J., and Robinson, K.L., 1996b, Neogene detachment and strike-slip faulting in the Salton Trough region and their geometric and genetic interrelationships. In Abbott, P.L. and Cooper, J.D. (eds.), Field Conference Guide 1996, Pacific Section AAPG, Guide Book 73, Pacific Section SEPM, Book 80, p. 263-276.

Fuis, G.S., W.D. Mooney, J.H. Healey, G.A. McMechan, and W.J. Lutter, 1982, Crustal structure of the Imperial Valley region, U. S. Geological Survey Professional Paper, 1254, 25-49.

Fuis, G. S., and Kohler, W. M., 1984, Crustal structure and tectonics of the Imperial Valley region, California. In Rigsby, C. A. (ed.), The Imperial Basin - Tectonics, Sedimentation, and Thermal Aspects. Los Angeles, California, Pacific Section S. E. P. M., p. 1-13.

Gastil, R.G., Neuhaus, J., Cassidy, M., Smith, J.T., Ingle, J.C., Jr., Krummenacher, D., 1999, Geology and paleontology of southwestern Isla Tiburon, Sonora, Mexico. Revista Mexicana de Ciencias Geologicas, v. 16, no. 1, p. 1-34.

Girty, G. H., and Armitage, A., 1989, Composition of Holocene Colorado River sand; an example of mixed-provenance sand derived from multiple tectonic elements of the Cordilleran continental margin. Journal of Sedimentary Petrology v. 59, p. 597-604.

Gjerde, M.W., 1982, Petrology and geochemistry of the Alverson Formation, Imperial County, California. Master of Science Thesis, San Diego State University, California, 85 p.

Guthrie, L.L., 1990, An internally standardized study of Cenozoic sand and sandstone compositions, Salton basin, southern California: Implications for rift basin evolution with emphasis on the Palm Spring and Imperial formations. Unpubl. M.S. Thesis, San Diego State University, CA, 180 p.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic. Science, v. 235, p. 1156-1167.

Heitmann, E. A., 2002, Characteristics of the Structural Fabric Developed at the termination of a major wrench fault. M.S. Thesis, San Diego State University, 77 p.

Hoover, R.A, 1965, Areal geology and physical stratigraphy of a portion of the southern Santa Rosa Mountains, San Diego County, California. Master of Science Thesis, Department of Geological Sciences, University of California, Riverside 81 p.

Hudnut, K.W., K.E. Sieh, 1989, Behavior of the Superstition Hills Fault during the past 330 years. Seismological Society of America Bulletin v. 79, p. 304-329.

Hudnut, K. W., Seeber, L., Pacheco, J., 1989, Cross-fault triggering in the November 1987 Superstition Hills earthquakes sequence, Southern California. Geoph. Res. Letters, v. 16, p. 199-202.

Ingle, J.C., 1974, Paleobathymetric history of Neogene marine sediments, northern Gulf of California. In Gastil, G., and Lillegraven, J. (eds.), Geology of Peninsular California. American Association of Petroleum Geologists, Pacific Section, Guidebook for Field Trips p. 121-138.

Janecke, S.U., Kirby, S.M., and Dorsey, R.J., 2003, New strand of the San Jacinto fault zone SW of the Salton Sea and a possible contractional step-over in the San Felipe Hills: A model to be tested. Geological Society of America Abstracts with Programs, v. 35, No. 4, p. 26.

Janecke, S.U., Kirby, S.M.*, Langenheim, V.E., Housen, B., Dorsey, R.J., Crippen, R.E., and Blom, R.G., 2004, Kinematics and evolution of the San Jacinto fault zone in the Salton Trough: Progress report from the San Felipe Hills. Geological Society of America Abstracts with Programs, v. 36, No. 5, p. 317.

Jefferson, G., and D. Peterson, 1998, Hydrothermal origin of the Fish Creek Gypsum, Imperial County, southern California. In L. Lindsay, W.G Hample (eds.), Geology and geothermal resources of the Imperial and Mexicali Valleys. San Diego Association of Geologists, San Diego, California, pp. 40-51.

Johnson, N. M., Officer, C. B., Opdyke, N. D., Woodard, G. D., Zeitler, P. K., and Lindsay, E. H., 1983, Rates of late Cenozoic tectonism in the Vallecito-Fish Creek basin, western Imperial Valley, California. Geology, v. 11, p. 664-667.

Kerr, D. R., 1982, Early Neogene continental sedimentation, western Salton Trough, California [M.S. thesis]. San Diego State University, San Diego, California, 138 p.

Kerr, D. R., 1984. Early Neogene continental sedimentation in the Vallecito and Fish Creek Mountains, western Salton Trough, California. Sedimentary Geology, v. 38, p. 217-246.

Kerr, D. R., and Kidwell, S. M., 1991, Late Cenozoic sedimentation and tectonics, western Salton Trough, California. In Walawender, M. J., and Hanan, B. B., (eds.), Geological Excursions in Southern California and Mexico. Department of Geological Sciences, San Diego State University, San Diego, California, p. 397-416.

Kirby, S.M., Janecke, S.U., Dorsey, R.J., and Layman, E.B., 2004a, Reorganization or initiation of the San Jacinto fault zone at 1 Ma: Evidence from syntectonic deposits in the San Felipe Hills, western Salton Trough, CA. Geological Society of America Abstracts with Programs, v. 36, No. 4, p. 37.

Kirby, S.M., Janecke, S.U., Dorsey, R.J., Housen, B.A., and McDougall, K., 2004, A 1.07 Ma change from persistent lakes to intermittent flooding and desiccation in the San Felipe Hills, Salton Trough, southern California. Geological Society of America Abstracts with Programs, v. 36, No. 5, p. 318.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California. In Winterer, E. L., Hussong, D. M., and Decker, R. W., (eds.), The Eastern Pacific Ocean and Hawaii. Geological Society of America, Boulder, Colorado, p. 499-522.

Lough, C. F., 1993, Structural evolution of the Vallecitos Mountains, Colorado Desert and Salton Trough geology. San Diego Association of Geologists, San Diego, California, p. 91-109.

Lough, C. F., 1998, Detachment faulting around Borrego Valley. In Geology and geothermal resources of the Imperial and Mexicali Valleys, edited by L. Lindsay, and W.G. Hample, pp. 40-51, San Diego Association of Geologists, San Diego, California.

Lough, C.F., and Stinson, A.L., 1991, Structural evolution of the Vallecito Mountains, southwest California. Geological Society of America Abstracts with Programs v. 23, no. 5, p. 246.

Lutz, A.T., and Dorsey, R.J., 2003, Stratigraphy of the Pleistocene Ocotillo Conglomerate, Borrego Badlands, southern California: Basinal response to evolution of the San Jacinto fault zone. Geological Society of America Abstracts with Programs, v. 35, No. 6, p. 248.

Lutz, A.T., Dorsey, R.J., and Housen, B.A., 2004, 0.5-0.6 Ma onset of uplift and transpressive deformation in the Borrego Badlands, southern California, due to initiation of the Coyote Creek Fault. EOS - Transactions of the American Geophysical Union. v. 85, don't know page # yet (Fall Meeting).

McDougall, K.A., Poore, R.Z., Matti, J.C., 1999, Age and paleoenvironment of the Imperial Formation near San Gorgonio Pass, Southern California. Journal of Foraminiferal Research, v. 29, p. 4-25.

Matti, J.C., Cox, B.F., Morton, D.M., Sharp, R.V., and King. T., 2002, Fault-bounded Neogene sedimentary deposits in the Santa Rosa mountains, southern California: Crustal stretching or transpressional uplift? Geological Society of America Abstracts with Programs. v. 34, no. 6, p.124.

Miller, J.M.G., and John, B.E., 1999, Sedimentation patterns support seismogenic low-angle normal faulting, southeastern California and western Arizona. Geological Society of America Bulletin, v. 111, p. 1350–1370.

Merriam, R.H., and O.L. Bandy, 1965, Source of upper Cenozoic sediments in the Colorado delta region. Journal of Sedimentary Petrology v. 35, p. 911-916.

Morley, E.R. Jr., 1963, Geology of the Borrego Mountain quadrangle and the western portion of Shell Reef quadrangle, San Diego County, California. Master of Arts Thesis, University of Southern California, Los Angeles 138 p.

Morton, D. M., and Matti, J. C., 1993, Extension and contraction within an evolving divergent strike-slip fault complex: the San Andreas and San Jacinto fault zones at their convergence in Southern California, In Powell, R. E., Weldon, R. J., and Matti, J. C. (eds.), The San Andreas fault system: displacement, palinspastic reconstruction, and geologic evolution. Geological Society of America Memoir, v. 178, p. 217-230.

Muffler, L.P.J., and B.R. Doe, 1968, Composition and mean age of detritus of the Colorado River delta in the Salton Trough, southeastern California. Journal of Sedimentary Petrology 38:384-399.

Opdyke, N.D., Lindsay, E.H., Johnson, N.M., and Downs, T., 1977, The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of the Anza-Borrego State Park, California. Quaternary Res., v. 7, p. 316-329.

Oskin, M.E.; Stock, J.M., and Martin-Barajas, A., 2001, Rapid localization of Pacific-North America plate motion in the Gulf of California. Geology, v. 29, p. 459-462.

Oskin, M., and Stock, J., 2003, Marine incursion synchronous with plate-boundary localization in the Gulf of California. Geology, v. 31, p. 23-26.

Pappajohn, S., 1980, Description of Neogene marine section at Split Mountain, easternmost San Diego County, California. Master of Science Thesis, San Diego State University, California 77 p.

Petersen, M. D., Seeber, L., Sykes, L. R., Nabelek, J. L., Armbruster, J. G., Paceco, J., Hudnut, K. W., 1991, Seismicity and fault interaction, southern San Jacinto fault zone and adjacent faults, Southern California; implications for seismic hazard. Tectonics, v. 10, p. 1187-1203.

Pettinga, J.R., 1991, Structural styles and basin margin evolution adjacent to the San Jacinto Fault Zone, southern California. Geological Society of America Abstracts with Programs, vol. 23, No. 5, p. 257.

Powell, R. E., Weldon, R. J., and Matti, J. C. (eds), 1993, The San Andreas fault system: Displacement, palinspastic reconstruction, and geologic evolution. Geological Society of America Memoir 178.

Quinn, H.A., and Cronin, T.M., 1984, Micropaleontology and depositional environments of the Imperial and Palm Spring formations, Imperial valley, California. In Rigsby, C. A. (ed.), The Imperial Basin - Tectonics, Sedimentation, and Thermal Aspects. Los Angeles, California, Pacific Section S.E.P.M., p. 71-85.

Remeika, P., 1995, Basin tectonics, stratigraphy, and depositional environments of the western Salton Trough detachment: the 1995 San Diego Association of Geologist's Field Trip Guide to Anza-Borrego Desert State Park, California. In P. Remeika and A. Sturz (eds.), Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California. Field Trip Guidebook and Volume for the 1995 San Diego Association of Geologists Field Trip to Anza-Borrego Desert State Park, Volume 1:3-45.

Remeika, P., Fischbein, I.W. , and Fischbein, S.A., 1988. Lower Pliocene petrified wood from the Palm Spring Formation, Anza-Borrego Desert State Park, California. Review of Palaeobotany and Palynology 56:183-198.

Remeika, P., and Fleming R.F., 1995, Cretaceous palynoflora and Neogene angiosperm woods from Anza-Borrego Desert State Park, California: implications for Pliocene climate of the Colorado Plateau and age of the Grand Canyon. In P. Remeika and A. Sturz (eds.), Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California. Field Trip Guidebook and Volume for the 1995 San Diego Association of Geologists Field Trip to Anza-Borrego Desert State Park, Volume 1:64-81.

Remeika, P. and Beske-Diehl, S., 1996, Magnetostratigraphy of the western Borrego Badlands, Anza-Borrego Desert State Park, California: Implications for stratigraphic age control, In Abbott, P. L. and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California. South Coast Geological Society Annual Field Trip Guide Book, No. 24, p. 209-220.

Rightmer, D.A., and Abbott, P.L., 1996, The Pliocene Fish Creek sturzstrom, Anza-Borrego Desert State Park, southern California. In Abbott, P. L. and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California. South Coast Geological Society Annual Field Trip Guide Book, No. 24, p. 165-184.

Rockwell, T., Loughman, C., Merifield, P., 1990, Late Quaternary rate of slip along the San Jacinto fault zone near Anza, Southern California. Jour. Geoph. Res. B, v. 95, n. 6, p. 8593-8605.

Ruisaard, C.I. 1979. Stratigraphy of the Miocene Alverson Formation, Imperial County, California. Master of Science Thesis, San Diego State University, California 125 p.

Ryter, D.W., 2002, Late Pleistocene kinematics of the central San Jacinto fault zone, southern California. Ph.D. dissertation, University of Oregon, Eugene, 137 p.

Sanders, C. O., 1993, Interaction of the San Jacinto and San Andreas fault zones, Southern California; triggered earthquake migration and coupled recurrence intervals. Science, v. 260, p. 973-976.

Sanders, C., and Magistrale, H., 1997, Segmentation of the northern San Jacinto fault zone, Southern California: Journal of Geophysical Research, v. 102, p. 27, 453-27,467.

Schultejann, P. A., 1984, The Yaqui Ridge antiform and detachment fault: Mid-Cenozoic extensional terrane west of the San Andreas fault. Tectonics, v. 3, p. 677-691.

Scheuing, D.F., Seeber, L., and Van Fossen, M., 1990, Structural and sedimentologic effects on detrital paleomagnetic directions and their bearing on Neogene block rotation in the San Jacinto fault zone, southern California. EOS - Transactions of the American Geophysical Union. v. 71, p. 1632.

Scheuing, D.F., and Seeber, L., 1991, Magnetostratigraphy of Neogene sediments in the San Jacinto fault zone, Southern California, and paleomagnetic evidence for block rotation. American Association of Petroleum Geologists annual convention. AAPG Bulletin, vol. 75, no. 3, p. 666-667.

Sharp, R. V., 1967, San Jacinto fault zone in the Peninsular Ranges of southern California. Geological Society of America Bulletin, v. 78, p. 705-730.

Shaller, P.J., and A.S. Shaller, 1996, Review of proposed mechanisms for sturzstroms (long-runout landslides In Abbott, P. L. and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California. South Coast Geological Society Annual Field Trip Guide Book, No. 24, 185-202.

Sharp, R. V., 1982, Tectonic setting of the Imperial Valley region. In The Imperial Valley, California, Earthquake of October 15, 1979. U. S. G. S. Professional Paper, P 1254, p. 5-14.

Steely, A., Janecke, S.U., Dorsey, R.J., and Axen, G.J., 2004a, Evidence for Late Miocene-Quaternary low-angle oblique strike-slip faulting on the West Salton detachment fault, southern California. Geological Society of America Abstracts with Programs, v. 36, No. 4, p. 37?

Steely, A.N., Janecke, S.U., and Dorsey, R.J., 2004b, Evidence for syn-depositional folding of Imperial-age synrift deposits above the west Salton detachment fault, Borrego Mountain area, southern California. Geological Society of America Abstracts with Programs, v. 36, No. 5, p. 317

Stinson, A.L., 1990, Structural deformation within the Pinyon Mountains, San Diego County, California. Master of Science Thesis, San Diego State University, California, 133 p.

Stinson, A. L., and Gastil, R. G., 1996, Mid- to Late-Tertiary detachment faulting in the Pinyon Mountains, San Diego County, California: A setting for long-runout landslides in the Split Mountain gorge area. In Abbott, P. L., and Seymour, D. C., (eds.), Sturzstroms and Detachment Faults, Anza-Borrego Desert State Park, California, Santa Ana, California, South Coast Geological Society Annual Field Trip Guide Book, No. 24, p. 221-244.

Stock, J. M., and Hodges, K. V., 1989, Pre-Pliocene extension around the Gulf of California and the transfer of Baja California to the Pacific plate. Tectonics, v. 8, p. 99-115.

Stump. T.E., 1972, Stratigraphy and paleoecology of the Imperial Formation in the western Colorado Desert. Master of Science Thesis, San Diego State University, California 132 p.

Tarbet, L.A., and W.H. Holman, 1944, Stratigraphy and micropaleontology of the west side of Imperial Valley. American Association of Petroleum Geologists Bulletin v. 28, p. 1781-1782.

Wells, D.L., 1987, Geology of the eastern San Felipe Hills, Imperial Valley, California: implications for wrench faulting in the southern San Jacinto fault zone [M.S. thesis]: San Diego, California, San Diego State University, 140 p.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere. Canadian Journal of Earth Science, v. 22, p. 108-125.

Wesnousky, S. G., 1986, Earthquakes, Quaternary faults, and seismic hazard in California. Journal of Geophysical Research, v. 91, p. 12, 587-12, 631.

Winker, C.D., 1987, Neogene stratigraphy of the Fish Creek - Vallecito section, southern California: implications for early history of the northern Gulf of California and Colorado delta. Ph.D. dissertation, University of Arizona, Tucson, 494 p.

Winker, C. D., and Kidwell, S. M., 1986, Paleocurrent evidence for lateral displacement of the Colorado River delta by the San Andreas fault system, southeastern California. Geology, v. 14, p. 788-791.

Winker, C. D., and Kidwell, S. M., 1996, Stratigraphy of a marine rift basin: Neogene of the western Salton Trough, California. In Abbott, P. L., and Cooper, J. D., (eds.), Field conference guidebook and volume for the annual convention, San Diego, California, May, 1996, Bakersfield, California, Pacific Section, American Association of Petroleum Geologist, p. 295-336.

Winker, C. D., and Kidwell, S. M., 2002, Stratigraphic evidence for ages of different extensional styles in the Salton Trough, southern California. Geological Society of America Abstracts with Programs, v. 34, No. 6, p. 83-84.

Winker, C. D., and Kidwell, S. M., 2003, Colorado River delta: 5 MYR-old tide-dominated, big-river delta in a tectonically evolving, oblique rift basin. Geological Society of America Abstracts with Programs, v. 35, No. 4, p. 28.

Woodard, G.D., 1974, Redefinition of Cenozoic stratigraphic column in Split Mountain Gorge, Imperial Valley, California. Am. Assoc. Petroleum Geologists Bulletin, v. 58, p. 521-539.

Woodring, W.P., 1931, Distribution and age of the marine Tertiary deposits of the Colorado Desert. Carnegie Institute of Washington Publication 418, p. 1-25.

Geology of the Anza-Borrego Desert Region- Figure Captions

Figure 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. ABF, Agua Blanca fault; BSZ, Brawley Spreading zone; CDD, Canada David detachment; CPF, Cerro Prieto fault; E, Ensenada; IF, Imperial fault; SAFZ, San Andreas fault zone; SD, San Diego; SGP, San Gorgonio Pass; SF, San Felipe; SJFZ, San Jacinto fault zone; SSPMF, Sierra San Pedro Martir fault; T, Tijuana; WB, Wagner basin. Shaded-relief map base courtesy of H. Magistrale.

Figure 2. Geologic Map of the Salton Trough Region. BB, Borrego Badlands; CF, Clark fault; CCF, Coyote Creek fault; EF, Elsinore Fault; ERF, Elmore Ranch Fault; EVF, Earthquake Valley fault; FCB, Fish Creek basin; IF, Imperial fault; SFF, San Felipe fault; SFH, San Felipe Hills; SHF, Superstition Hills fault; SMF, Superstition Mt fault; TBM, Tierra Blanca Mts; WP, Whale Peak. Map compilation courtesy of L. Seeber.

Figure 3. Generalized stratigraphic column for the Fish Creek-Vallecito section, adapted from Winker and Kidwell (1996). 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 (1995, 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).

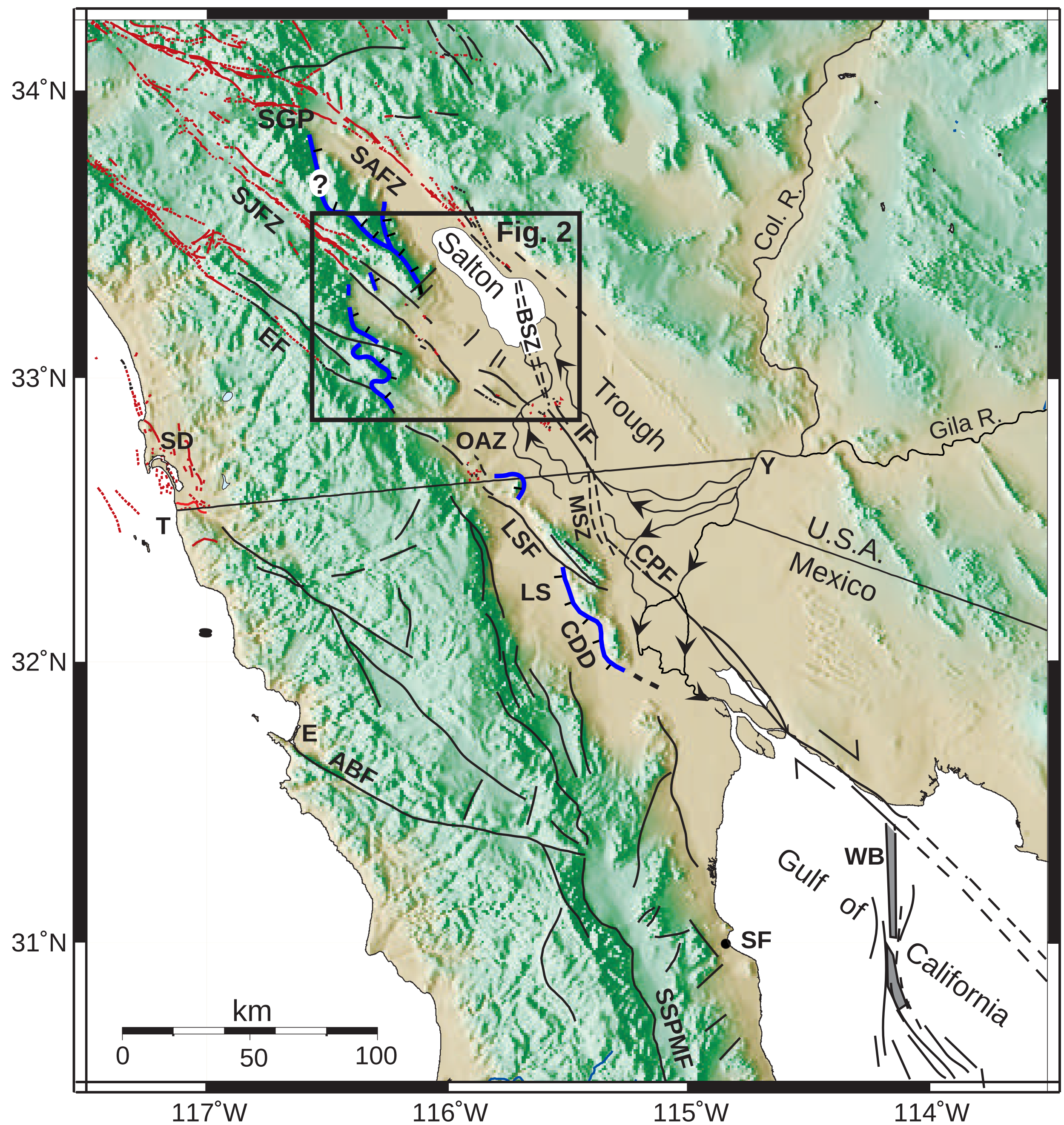
Figure 4. Stratigraphy of the northwestern Salton Trough, modified from Abbott (1968), Dibblee (1954) and Sharp (1982). Age of lower Palm Spring Group is based on micropaleontologic study of Quinn and Cronin (1984); age of the base of the Ocotillo Conglomerate is based on paleomagnetic studies by Brown et al. (1991) and Remeika and Beske-Diehl (1996).

Figure 5. Cross-section sketches showing the partial evolution of a detachment fault and upper-plate (supradetachment) sedimentary basin created by regional extension (from Wernicke, 1985). **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 on a series of closely spaced normal faults that disrupt sedimentation in the basin. 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.

Figure 6. Photographs showing examples of sedimentary rocks and geomorphology in the western Salton Trough region. **A.** 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. **B.** Tan fine-grained marine mudstone capped by oyster beds in the lower Imperial Group, Fish Creek – Vallecito basin; white patch in distance is Fish Creek Gypsum in the western Fish Creek Mts. **C.** Channelized sandstone (tan color) and red mudstone of the Olla Formation (Palm Spring Group) that were deposited in the ancestral Colorado River delta plain. **D.** 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).

Figure 7. Paleogeographic reconstructions of sedimentary basins and faults in the Salton Trough and northern Gulf of California since the end of Miocene time, redrafted from Winker (1987) with modifications from Axen (1995), Axen and Fletcher (1998), and Oskin et al. (2001). Southern California and northern Baja California have been translating to the northwest relative to stable North America since localization of the plate boundary in the Gulf of California at ~6.0 Ma (Oskin et al., 2001; Oskin and Stock, 2003). **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. CU = Sierra Cucapas; FCV = Fish Creek - Vallecito basin; IH - Indio Hills; SF = San Felipe; SFH = San Felipe Hills; 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.



34°N
33°N
32°N
31°N
117°W
116°W
115°W
114°W
SGP
SAFZ
SJFZ
EF
Fig. 2
Salton
BSZ
Trough
Col. R.
Gila R.
SD
T
OAZ
IF
Y
MSZ
LSF
CPF
U.S.A.
Mexico
LS
CDD
E
ABF
WB
Gulf of California
SF
SSPMF
km
0
50
100

Figure 1

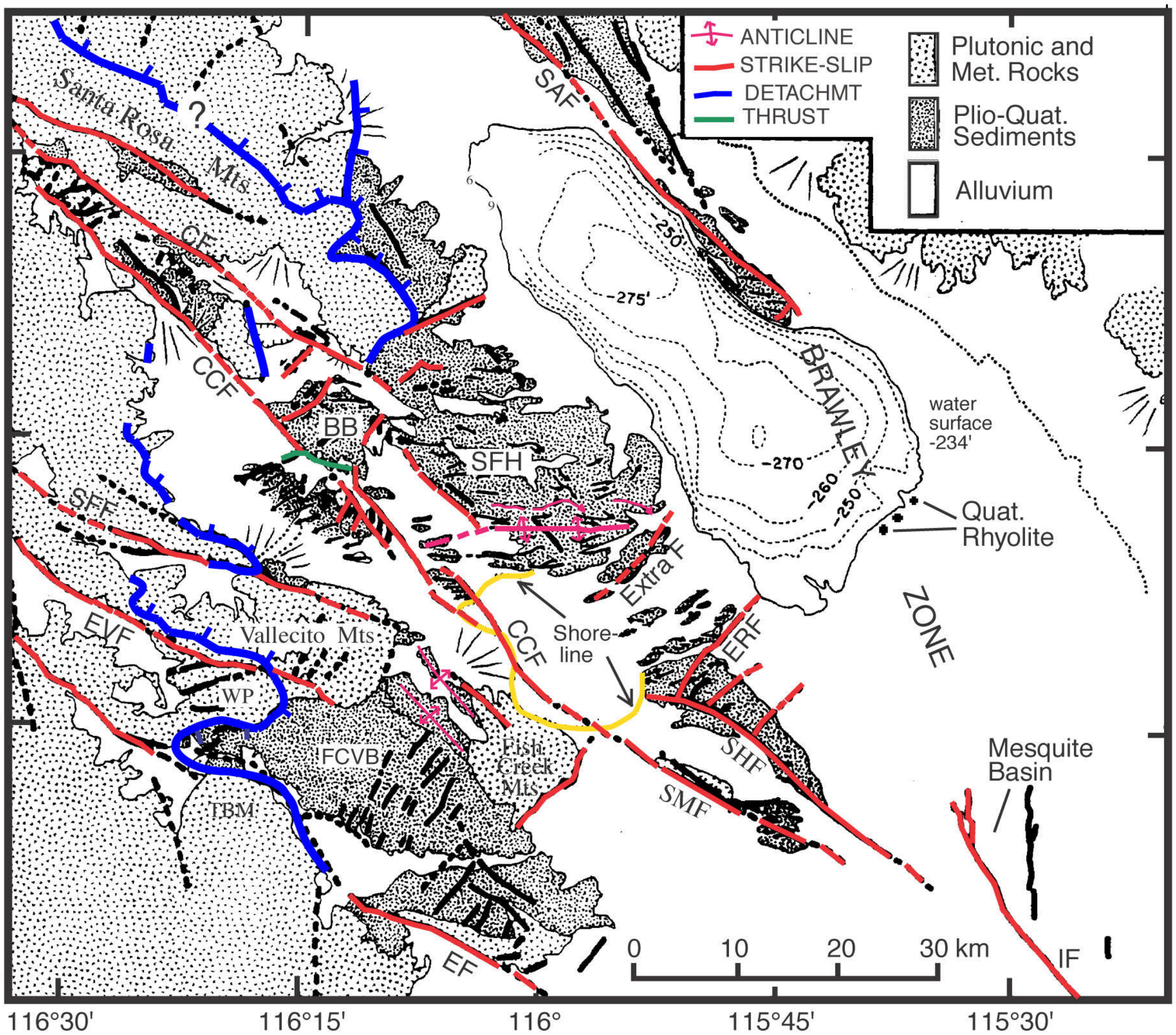
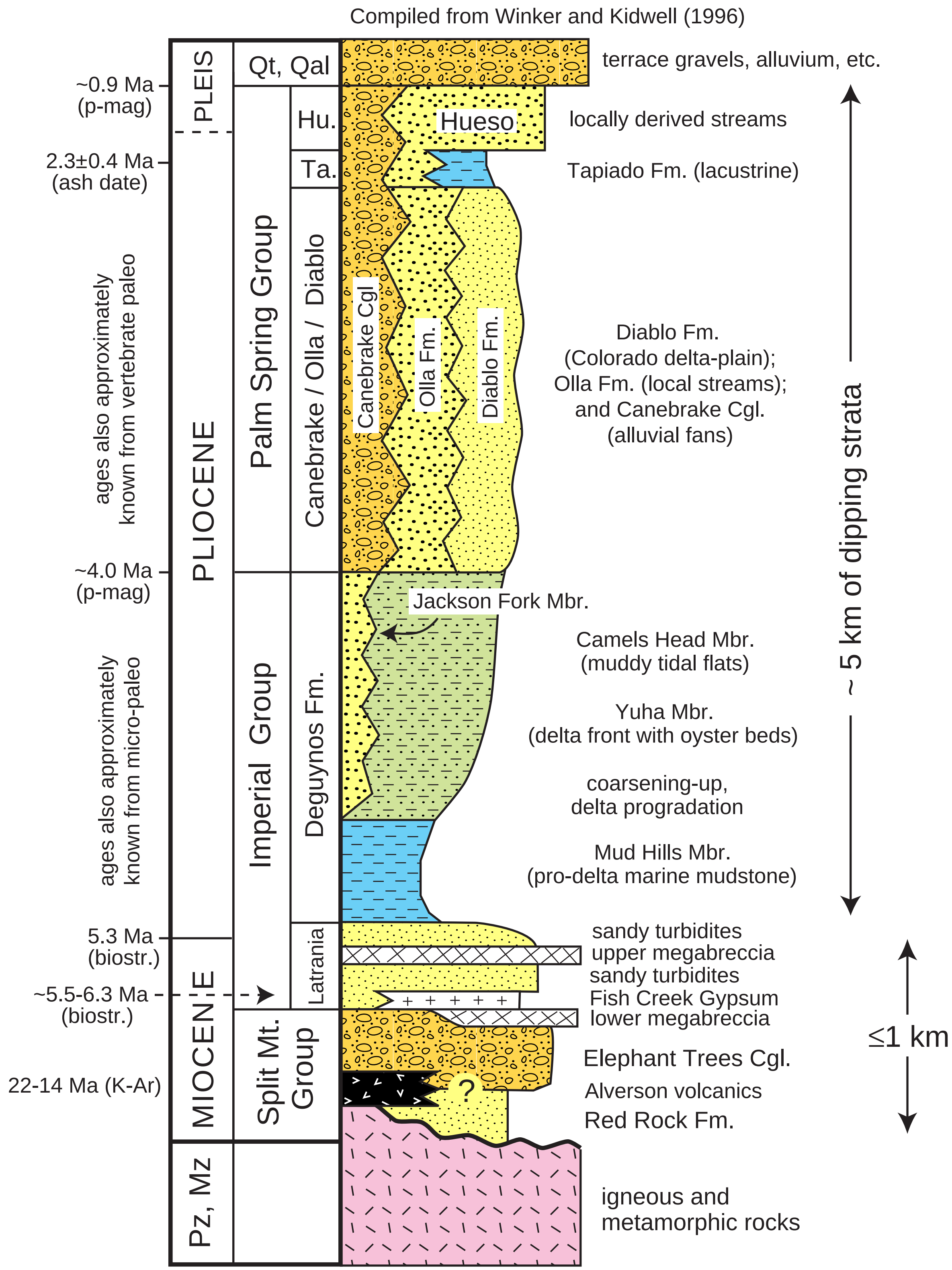

ANTICLINE
STRIKE-SLIP
DETACHMT
THRUST
Plutonic and Met. Rocks
Plio-Quat. Sediments
Alluvium
Santa Rosa Mts
SAF
CF
CCF
BB
SFH
BRAWLEY
ZONE
water surface -234'
-275'
-270
-260
-250
Quat. Rhyolite
SFF
Extra F
EVF
Vallecito Mts
WP
Shore-line
ERF
FCVB
Fish Creek Mts
SHF
SMF
TBM
Mesquite Basin
EF
IF
0
10
20
30 km
33° 30'
33° 15'
33°
32° 45'
116°30'
116°15'
116°
115°45'
115°30'

Figure 2



Compiled from Winker and Kidwell (1996)
~0.9 Ma
(p-mag)
2.3±0.4 Ma
(ash date)
ages also approximately known from vertebrate paleo
~4.0 Ma
(p-mag)
ages also approximately known from micro-paleo
5.3 Ma
(biostr.)
~5.5-6.3 Ma
(biostr.)
22-14 Ma (K-Ar)
PLEIS
PLIOCENE
MIOCENE
Pz, Mz
Qt, Qal
Palm Spring Group
Hu.
Ta.
Canebrake / Olla / Diablo
Imperial Group
Deguynos Fm.
Latrania
Split Mt. Group
Hueso
Canebrake Cgl
Olla Fm.
Diablo Fm.
Jackson Fork Mbr.
terrace gravels, alluvium, etc.
locally derived streams
Tapiado Fm. (lacustrine)
Diablo Fm.
(Colorado delta-plain);
Olla Fm. (local streams);
and Canebrake Cgl.
(alluvial fans)
Camels Head Mbr.
(muddy tidal flats)
Yuha Mbr.
(delta front with oyster beds)
coarsening-up,
delta progradation
Mud Hills Mbr.
(pro-delta marine mudstone)
sandy turbidites
upper megabreccia
sandy turbidites
Fish Creek Gypsum
lower megabreccia
Elephant Trees Cgl.
Alverson volcanics
Red Rock Fm.
igneous and
metamorphic rocks
~ 5 km of dipping strata
≤1 km

Figure 3

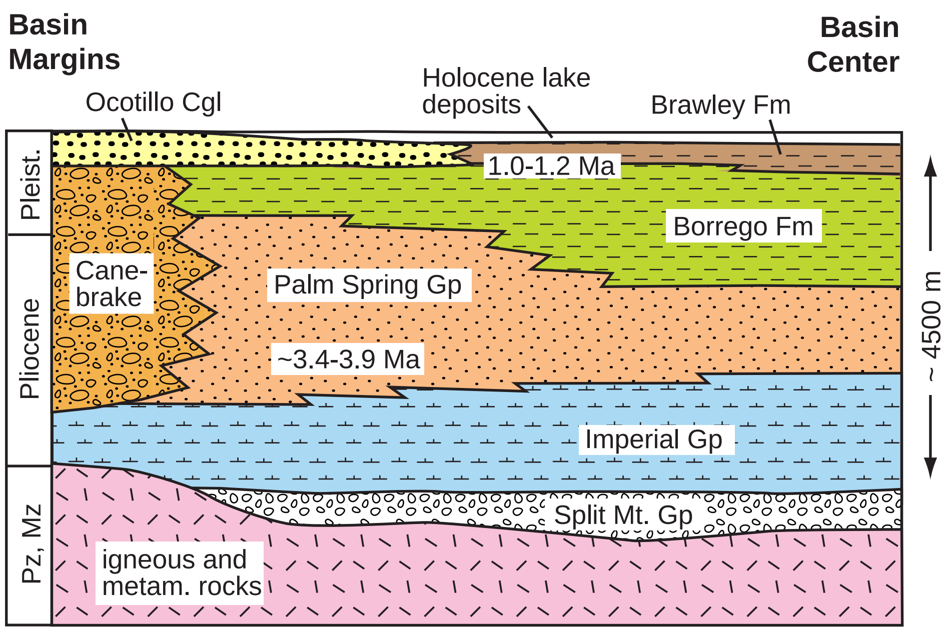

Basin Margins
Basin Center
Ocotillo Cgl
Holocene lake deposits
Brawley Fm
Pleist.
1.0-1.2 Ma
Borrego Fm
Cane-brake
Palm Spring Gp
Pliocene
~3.4-3.9 Ma
~ 4500 m
Imperial Gp
Split Mt. Gp
Pz, Mz
igneous and metam. rocks

Figure 4

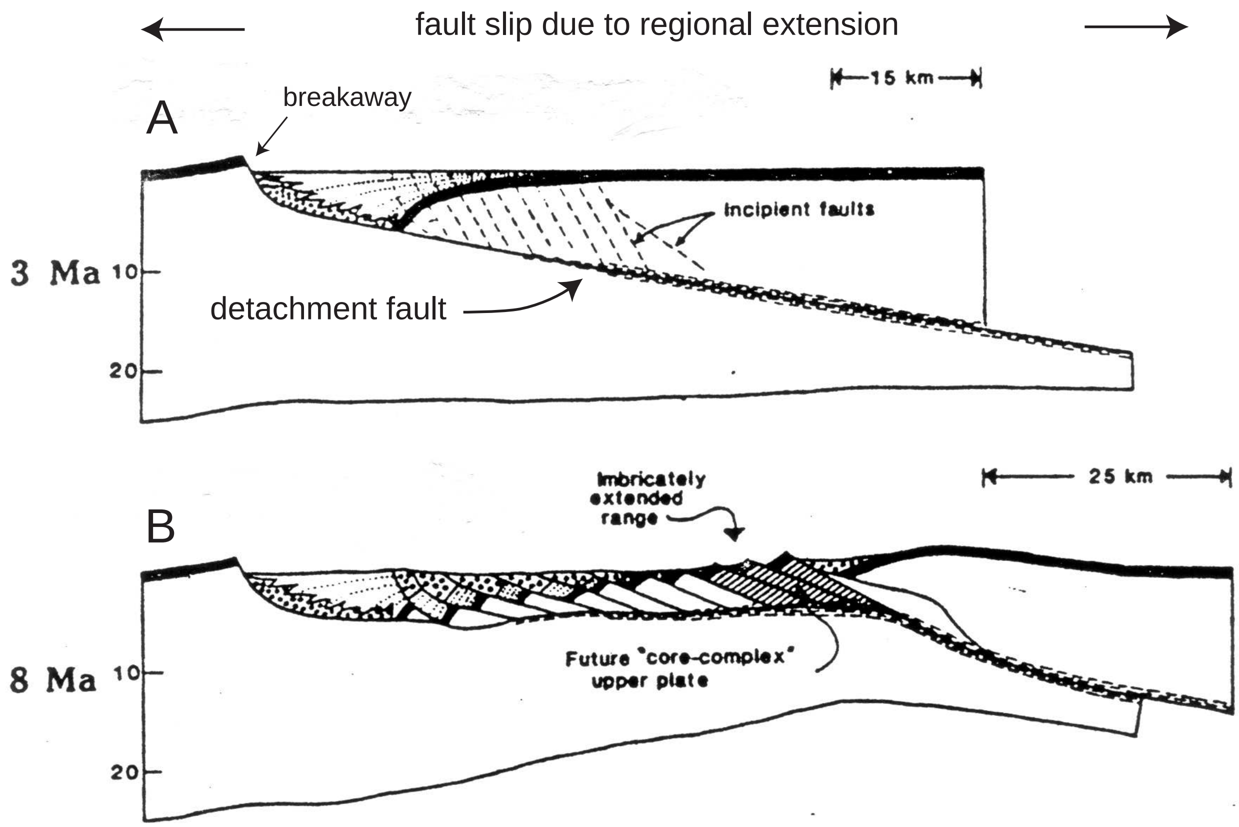

fault slip due to regional extension
15 km
A
breakaway
incipient faults
3 Ma
10
detachment fault
20
25 km
Imbricately
extended
range
B
Future "core-complex"
upper plate
8 Ma
10
20

Figure 5

Figure 6A

Figure 6B

Figure 6C

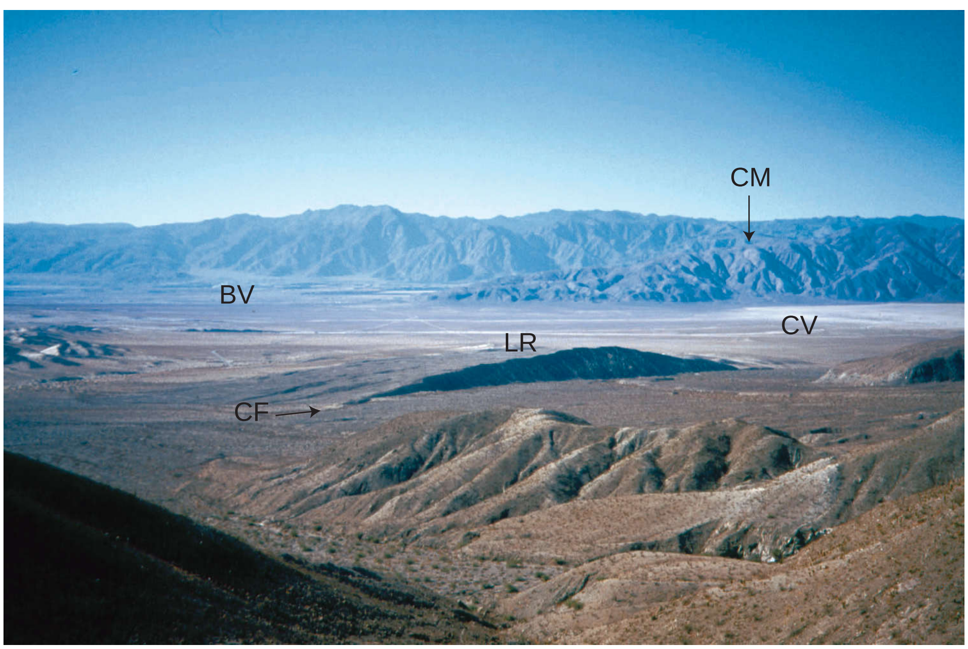
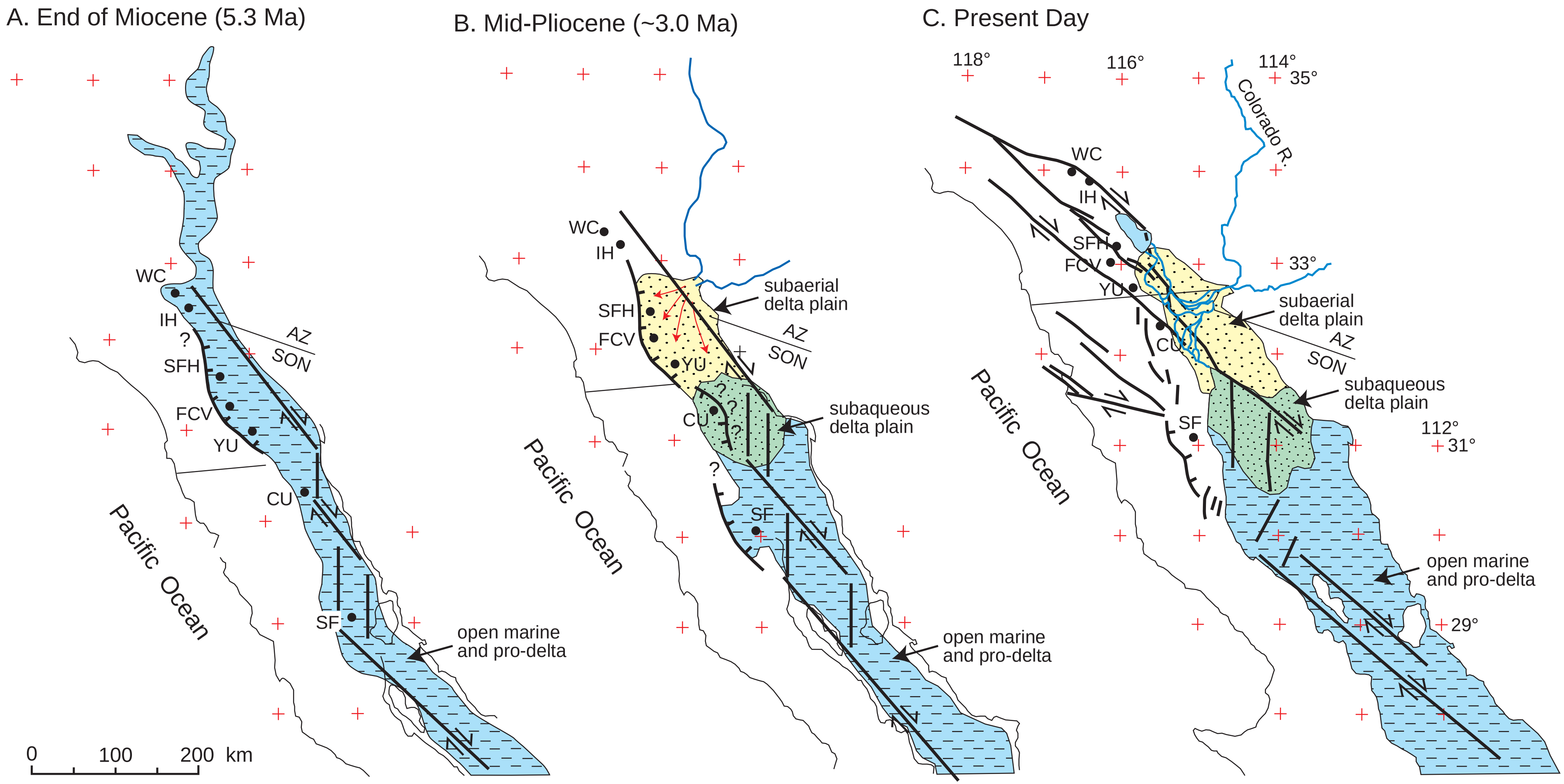


Figure 6D



A. End of Miocene (5.3 Ma)
WC
IH
?
SFH
FCV
YU
CU
SF
AZ
SON
Pacific Ocean
open marine
and pro-delta
0
100
200 km
B. Mid-Pliocene (~3.0 Ma)
WC
IH
SFH
FCV
YU
CU
SF
?
subaerial
delta plain
AZ
SON
subaqueous
delta plain
Pacific Ocean
open marine
and pro-delta
C. Present Day
118°
116°
114°
35°
Colorado R.
33°
112°
31°
29°
WC
IH
SFH
FCV
YU
CU
SF
subaerial
delta plain
AZ
SON
subaqueous
delta plain
Pacific Ocean
open marine
and pro-delta

Figure 7