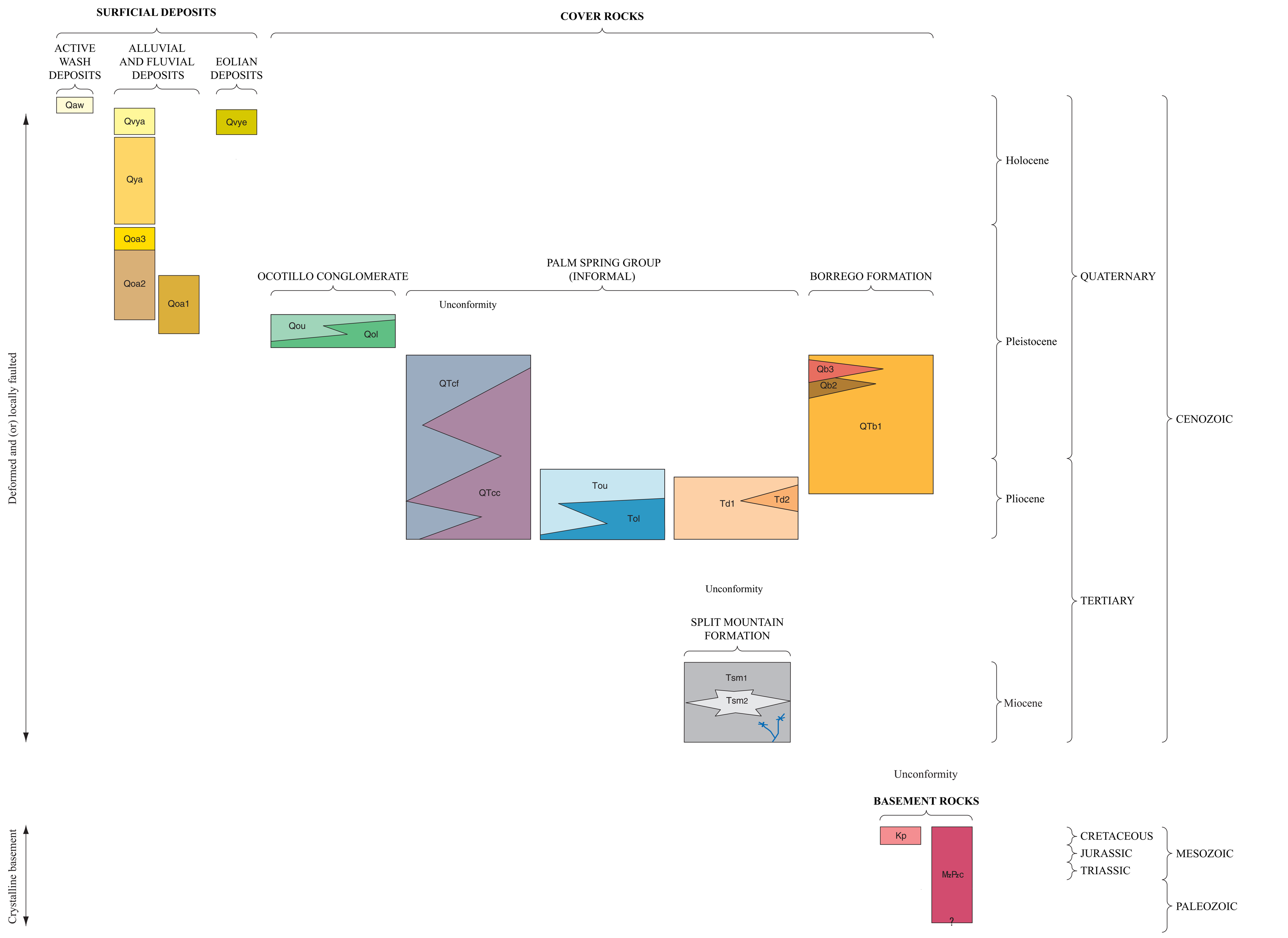
CORRELATION OF MAP UNITS



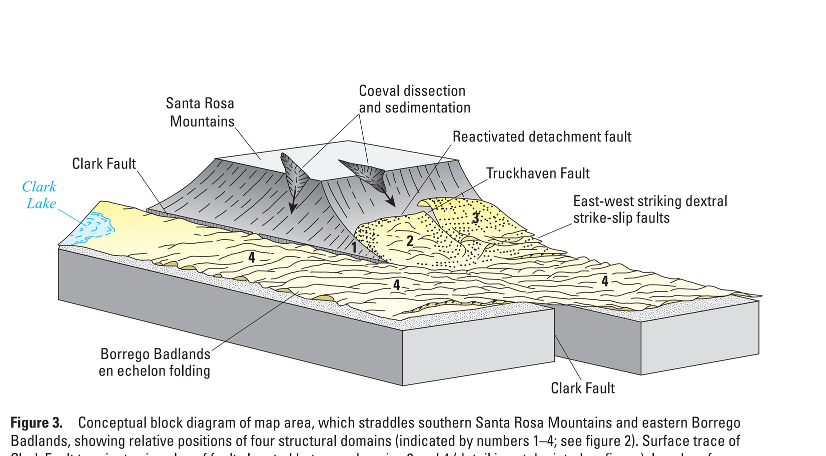


Figure 3. Conceptual block diagram of map area, which straddles southern Santa Rosa Mountains and eastern Borrego Badlands, showing relative positions of four structural domains (indicated by numbers 1–4; see figure 2). Surface trace of Clark Fault terminates in splay of faults located between domains 2 and 4 (detail is not depicted on figure). In subsurface, Clark Fault is projected to continue southeastward where it is obscured by decoupled cover strata. East and northeast of exposed tip of Clark Fault, cover strata are displaced northward onto flank of Santa Rosa Mountains along thrust-reactivated section of West Salton Detachment Fault. Truckhaven Fault represents sinistral tear structure in thrust sheet (see figure 4). In foreground, structural domain 4 consists of complex deformation of eastern Borrego Badlands over multiple shallow-level thrust décollements and associated folds. Diagram is not to scale; view is to north-northwest.

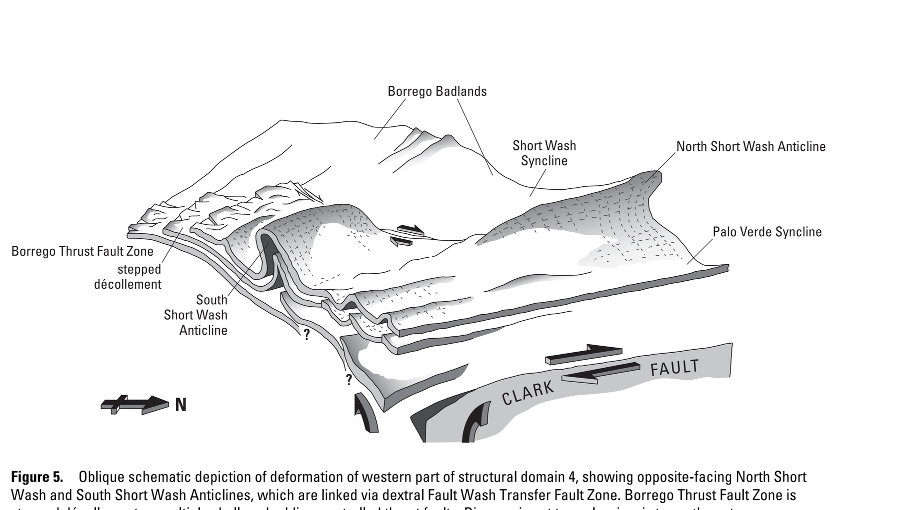


Figure 5. Oblique schematic depiction of deformation of western part of structural domain 4, showing opposite-facing North Short Wash and South Short Wash Anticlines, which are linked via dextral Fault Wash Transfer Fault Zone. Borrego Thrust Fault Zone is stepped décollement on multiple shallow, bedding-controlled thrust faults. Diagram is not to scale; view is to southwest.

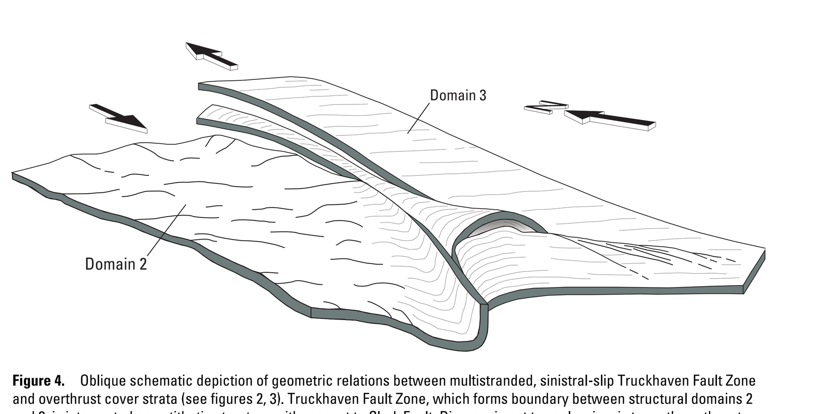


Figure 4. Oblique schematic depiction of geometric relations between multistranded, sinistral-slip Truckhaven Fault Zone and overthrust cover strata (see figures 2, 3). Truckhaven Fault Zone, which forms boundary between structural domains 2 and 3, is interpreted as antithetic structure with respect to Clark Fault. Diagram is not to scale; view is to north-northeast.

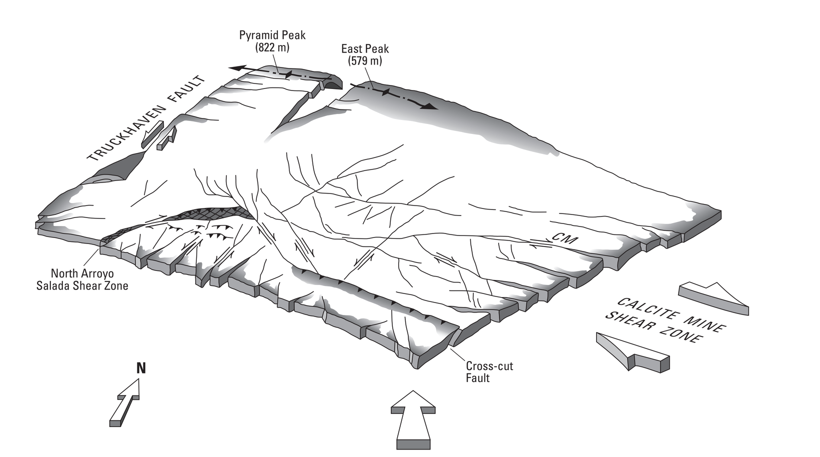


Figure 6. Oblique schematic depiction of deformation patterns within structural domain 3, showing major structures that accommodate internal deformation within overthrust cover strata above thrust-reactivated detachment fault (not shown). Paired large white half arrows show sense of slip along major structures. Large arrow in foreground denotes direction of overthrust northward. North-trending wall of overthrust cover strata, positioned on south flank of Santa Rosa Mountains, is delineated by anticline at top of diagram. Note locations of informally named "Pyramid Peak" and "East Peak". Label 'CM' shows location of Calcite Mine. Diagram is not to scale; view is to north-northwest; m, meters.

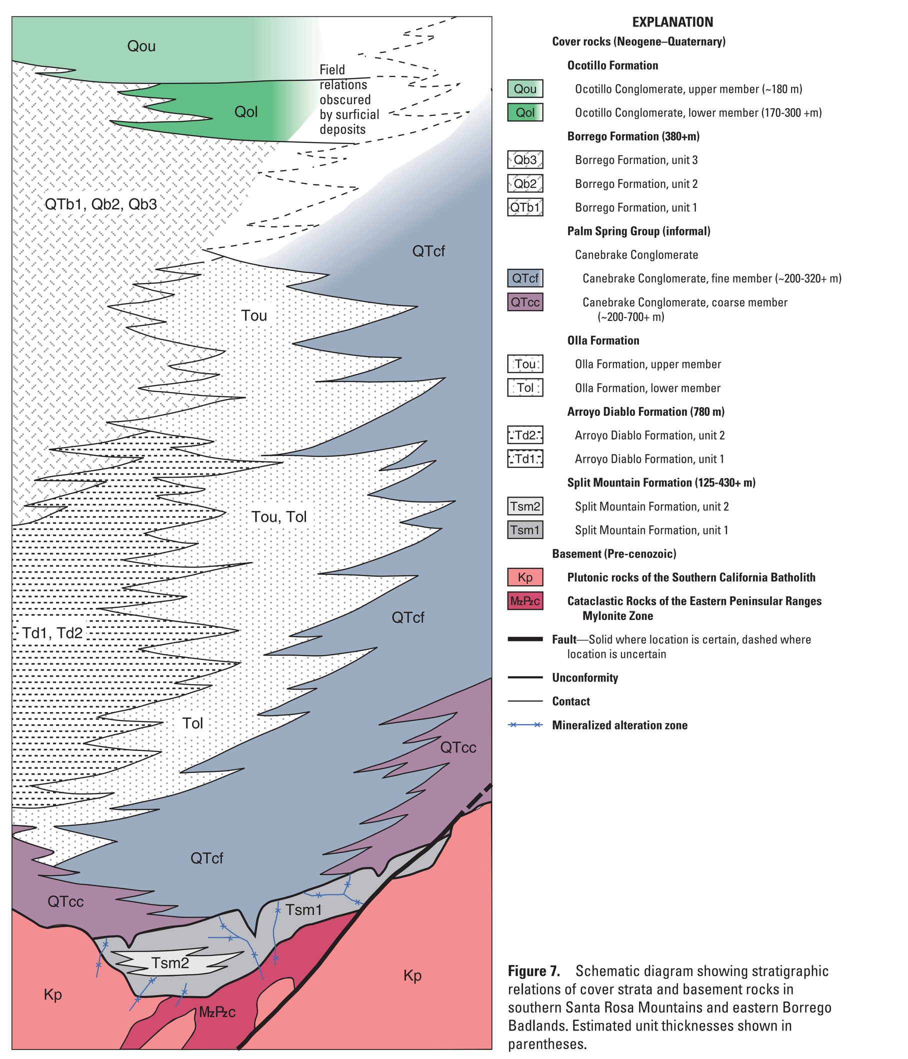


Figure 7. Schematic diagram showing stratigraphic relations of cover strata and basement rocks in southern Santa Rosa Mountains and eastern Borrego Badlands. Estimated unit thicknesses shown in parentheses.

DESCRIPTION OF MAP UNITS

[ka, kilo-annum; Ma, mega-annum]

SURFICIAL DEPOSITS

ACTIVE WASH DEPOSITS

Qaw — **Active wash deposits, undifferentiated (uppermost Holocene)**—Alluvial gravel, sand, and silt, in active stream channels (0–~0.05 kilo-annum [ka])[1]

ALLUVIAL AND FLUVIAL DEPOSITS

Qvya — **Very young alluvial deposits (uppermost to middle Holocene)**—Alluvial gravel, sand, and silt. Terrain is locally dissected; undeformed except where disturbed by active faulting (0.05–4.0 ka)[1]

Qya — **Young alluvial deposits (middle Holocene to uppermost Pleistocene)**—Alluvial gravel and sand. Terrain is dissected; undeformed except where disturbed by active faulting (4.0–12 ka)[1]

Old alluvial fan deposits—Divided into the following subunits:

Qoa3 — **Old alluvial fan deposits, subunit 3 (upper Pleistocene)**—Alluvial gravel and sand. Terrain is dissected; locally deformed and faulted (estimated age range, 12–70 ka)[1]

Qoa2 — **Old alluvial fan deposits, subunit 2 (upper to middle Pleistocene)**—Alluvial gravel and sand. Terrain is dissected; locally deformed and faulted (estimated age range, 70–200 ka)[1]

Qoa1 — **Old alluvial fan deposits, subunit 1 (upper to middle Pleistocene)**—Alluvial gravel and sand. Terrain is dissected; locally deformed and faulted (estimated age range, 70–200 ka)[1]

EOLIAN DEPOSITS

Qvye — **Very young eolian deposits (uppermost to middle Holocene)**—Light-colored, medium to very fine sand. Draped over eroded and (or) dissected cover strata terrain. Undeformed except where disturbed by active faulting (0–~4.0 ka)[1]

COVER ROCKS

OCOTILLO CONGLOMERATE

Ocotillo Conglomerate—Unit was first named by Dibblee (1954); Lutz and others (2006) informally subdivided formation into four lithofacies on the basis of field attributes. Unit crops out extensively in southwestern and southern parts of study area; here, unit is subdivided informally into lower and upper members. This field-based subdivision is not directly equivalent to that adopted by Lutz and others (2006). Base of unit is dated at 1.05±0.03 Mega-annum (Ma), and top, at ~0.5 Ma, on the basis of magnetostratigraphy, rich Irvingtonian vertebrae fauna, and presence of both the Bishop ash (~0.76 Ma) and the Thermal Canyon ash (~0.74 Ma) (Miller and others, 1991; Remeika and Jefferson, 1993; Jefferson and Remeika, 1994; Remeika and Beske-Diehl, 1996; Bell and others, 2004; Lutz and others, 2006). We tentatively correlate distinctive tuff bed mapped near base of lower member with airfall tuff in Vallecito–Fish Creek Mountains area dated by fission-track analysis (zircons) at 0.9 Ma (Johnson and others, 1983). Mapped as the following two members:

Qou — **Upper member (upper Pleistocene)**—Distinctive, weakly cemented, gray to light-brown conglomerate and sandstone, derived from local sources. In western part of study area, overlies the lower member conformably; best exposed along south-facing escarpment, immediately northwest of Palo Verde Wash and Short Wash junction. To east, near Seventeen Palms, sandstone-dominated upper member rests conformably on upper part of the Borrego Formation. No fossil material has been recovered from member, but stratigraphic correlation with respect to Lutz and others (2006) study confirms late Pleistocene age. Member is youngest cover-strata unit in map area. Laterally, member may be equivalent to youngest member of the Canebrake Conglomerate of this study, the fine-grained member (QTcf), now deeply dissected and perched at higher elevations on south-facing flank of Santa Rosa Mountains between Smoke Tree Canyon and Arroyo Salada canyon, but no direct stratigraphic correlations are possible. Depositional environment is likely alluvial fan to fluvial braided-river and (or) floodplain setting

Qol — **Lower member (upper Pleistocene)**—Basal strata; undifferentiated assemblage of pebble conglomerate and sandstone and upper sequence of light-pink to grayish-brown sandstone and gray to light-reddish-brown siltstone and mudstone. Several distinctive green marker beds of sandstone and siltstone and a tuff marker bed are found within member. Sediment of member is mostly derived from local source terrain, but member also includes strata of mixed source affinity. Basal contact with lacustrine beds of the Borrego Formation is sharp and conformable. West of Fault Wash, lower member predominantly consists of small pebble conglomerate and coarse-grained quartzofeldspathic sandstone. Farther east from Fault Wash toward Palo Verde Wash, basal sandstones are finer grained and micaceous. Undifferentiated strata of lower member likely represent series of interrelated paleodepositional settings, ranging from distal alluvial fan sediments (conglomerate and sandstone) to fluvial braided-stream and (or) floodplain deposits (sandstone, siltstone, mudstone) to lacustrine and playa deposits (claystone, mudstone, siltstone, and sandstone). No attempt was made to document complex interfingering of these lithofacies (compare with Lutz and others 2006). East of Palo Verde Wash, lower member laterally interfingers with lacustrine strata of upper part of the Borrego Formation. Only thin sandstone beds of lower member are mapped west-northwest of Seventeen Palms. Basal conglomerate and sandstone beds south of Short Wash are overlain by light-pink to grayish-brown sandstone, gray to reddish-brown siltstone and mudstone, and claystone beds that have interbedded green sandstone and siltstone marker beds. Northwest of Short Wash, basal conglomerates and sandstones are replaced laterally by siltstone- and mudstone-dominated succession, whereas overlying beds include light-green to yellowish-gray micaceous sandstones and alternating brown siltstone and mudstone. Upper contact with overlying conglomerate and sandstone of upper member is sharp and conformable

PALM SPRING GROUP

Palm Spring Group (informal)—The Pliocene to Pleistocene Palm Spring Group was informally proposed by Cassiliano (2002) but not formally gazetted into the stratigraphic Lexicon. The informally proposed new hierarchy was established on the basis of fieldwork in Fish Creek–Vallecito Creek basin (fig. 1, on sheet 1) of western Salton Trough, defining three new formations and elevating two existing subunits to the rank of formation. These revisions are mostly based on earlier work and stratigraphic hierarchy of Woodring (1932), Dibblee (1954, 1984), and Winker (1987). Cassiliano (2002) extended this stratigraphic revision to include other areas within Salton Trough. This proposed stratigraphic hierarchy is most appropriate within map area, where the Palm Spring Group is represented by three of these redefined, laterally interfingering formations: the Canebrake Conglomerate, the Arroyo Diablo Formation, and the Olla Formation. Field mapping in this study has further established two informal, lithologically distinct but interfingering members within each formation. The Palm Spring Group is mapped as the following formations:

Canebrake Conglomerate—Type section is located in southeastern Vallecito Mountains (Dibblee, 1954). Dibblee (1954) also described presence of formation within southern part of Santa Rosa Mountains map area, referring to it as coarse-grained basin-margin formation and facies equivalent of the more distal Palm Spring Formation (as defined before Cassiliano (2002) proposed reassignment). Cassiliano (2002) informally included formation as coarse-grained basin-margin facies within the Palm Spring Group. In map area, the formation is further subdivided informally into a coarse-grained member and a fine-grained member, which are, in part, laterally equivalent as documented by interfingering. No diagnostic fossils have been collected from formation. Its stratigraphic position, as well as its regional correlations, indicates that formation likely ranges from middle Pleistocene to lower Pliocene. Basal contact of formation with the underlying Split Mountain Formation is generally gradational for about 3–10 meters (m) but locally is sharp, with some angular discordance. Formation has traditionally been interpreted as alluvial fan deposit (Dibblee 1954, 1984). Coarse-grained member facies is equivalent to proximal, fan-head depositional setting, whereas fine-grained member is interpreted as being typical of more distal, middle-fan to fan-base depositional settings. Coarse-grained member is predominantly made up of debris-flow beds and distributary-fluvial-channel deposits, whereas fine-grained member is interpreted to be dominated by sheet-wash and distributary-fluvial-channel deposits that transition to braided-stream floodplain setting. In map area, decrease in conglomerate clast size occurs with lateral transition from coarse- to fine-grained member; basinward lateral transition into bedded sandstone of the Olla Formation is indicative of basin-margin alluvial fan to fluvial-floodplain depositional environment. Comparable depositional setting can be observed at foot of west-facing rangefront of Santa Rosa Mountains, adjacent to Clark Lake, immediately northwest of map area. Mapped as the following two members:

QTcf — **Fine-grained member (middle Pleistocene to lower Pliocene)**—Light-gray to light-yellowish-gray cobble and pebble conglomerate; conglomeratic sandstone, gradationally to moderately well bedded, typically laminated, cross stratified and calcite cemented. East of upper reaches of Arroyo Salada canyon, strata are exposed in deeply dissected and canyoned terrain. Sequence here consists of gradationally bedded, calcite-cemented conglomeratic sandstone. Conglomerate is typically confined to lenses or discrete horizons, and clasts range from small pebble to cobble size, with rare boulders. Poor parallel lamination, cross-lamination, and rare cross-stratification are present. Many high bluffs are honeycombed in response to case hardening of outer 1–3 m of calcite-cemented rock. Farther east in area near Calcite Mine, underlies the coarse member, whereas to south of mine area, laterally transitions into the Olla Formation. West of Arroyo Salada in upper reaches of Coachwhip Canyon, below 1,400 feet (ft) contour, dissected terrain provides good exposure of equivalent stratigraphic level of member mapped farther east of Arroyo Salada. In central part of map area, member is more complexly deformed; to north and northwest, member is characterized by local internal (within member) unconformities, indicative of coeval deformation and erosional dissection during sedimentation of succession. Southward from about 1,400-ft contour level, coherent stratigraphic succession interfingers with the Olla Formation. Strata of member mapped near State Highway S22 are better stratified internally, having more clearly defined bedding, lamination, and cross-stratification. Conglomerate component is subordinate to sandstone. In southern part of Smoke Tree Canyon, north of Highway S22, strata of member are more thinly stratified and indistinctly bedded, with greater proportion of conglomerate clasts. West of Smoke Tree Canyon, member grades laterally into coarse-grained member. Outcrop exposures in northwestern part of map area, between Palo Verde Wash and Smoke Tree Canyon, are generally poor because of slope colluvium. Faulted basal contact, however, is well exposed along Smoke Tree Fault, and it is interpreted as thrust-reactivated part of West Salton Detachment Fault. In this area, strata of both members (that is, both fine- and coarse-grained members) are oriented with moderate to steep dips above basal low-angle fault. Fine-grained member generally dips to south and forms broad, open, southwest-plunging fold in northwestern part of map area, first named Santa Rosa Anticline by Dibblee (1954)

[1]Age estimates adapted from W.B. Bull (1991; also, written commun., 1987).

QTcc — **Coarse-grained member (middle Pleistocene to lower Pliocene)**—Light-gray to light-yellowish-gray boulder and cobble conglomerate that has pebble- to sand-sized matrix; typically crudely bedded, rarely laminated or cross-stratified; calcite cemented. Conglomerate beds range from unsorted to normal and reverse graded. Most widely distributed rock unit across northern part of map area. Best exposures are found in elevated northeast quadrant of map area, immediately east of Truckhaven Fault, surrounding 2,697-ft "Pyramid Peak". Locally rests unconformably on highly fractured to brecciated granodiorite and diorite of Peninsular Ranges batholith (Kp) and both conformably and locally unconformably on Split Mountain Formation (Tsm1 and Tsm2) in northeastern part of map area. Similarly, excellent exposures are found in canyon terrain near Calcite Mine area; in canyon south of termination of Truckhaven Fault; west of upper reaches of Arroyo Salada canyon; in east branch of Coachwhip Canyon; and in Smoke Tree Canyon

Olla Formation—Name first proposed informally by Winker (1987) and informally adopted by Cassiliano (2002); named for Olla Wash in Fish Creek–Vallecito Mountains area of western Salton Trough. Typically, sediment was derived from two distinct source regions: local sources (dominant component) and Colorado River sources (subordinate component). Throughout region (including map area), mineralogy, texture, and coloration allow for easy field separation of respective source components. On the basis of regional correlation and stratigraphic position, formation is upper to lower Pliocene in age (Cassiliano, 2002). Within map area, formation is divided informally into upper and lower members. Where stratal packages could be identified and separated out at map scale, contacts between interfingering members are depicted approximately. However, in field, interfingering relations typically are more complex. Distal tongues of formation reach out to east and southeast and are interbedded with strata of the Arroyo Diablo Formation. Both members of formation are well bedded, laminated, and crossbedded; locally organized into upward-thickening and upward-thinning cycles, indicative of depositional setting that ranges from proximal fluvial-braided stream to delta-plain environment. Mapped as the following two members:

Tou — **Upper member (upper to lower Pliocene)**—Grayish-green micaceous sandstone and siltstone and interbedded dark-brown to reddish-brown or dark-green mudstone and claystone. Sandstone is indistinctly bedded; bed thicknesses range from thin to moderately thick. Calcite cementation is ubiquitous, and, in vertical canyon walls, weathering profile is characteristically bulbous, with "onion-skin" exfoliation of upper, finer grained parts of individual beds. Mudstone and claystone intervals are predominantly Colorado River sourced, whereas sandstones are of mixed provenance. Siltstone intervals between sandstone beds commonly contain concentrations of irregularly shaped light-gray calcareous nodules that probably are disrupted paleocaliche horizons. Intricately interfingers with strata of the Arroyo Diablo Formation. Age of member is late to early Pliocene

Tol — **Lower member (upper to lower Pliocene)**—Light-gray to greenish-gray, thick- to thin-bedded, parallel laminated and ripple laminated, crossbedded micaceous sandstone and subordinate interbedded brown to purplish siltstone and mudstone beds. Sandstones are calcite cemented and weather to rusty or orangeish brown. Bedding locally appears uniform and parallel, but across distances of hundreds of meters, beds are lenticular and help to define facies transitions. Transitions laterally into strata of the Canebrake Conglomerate. Sediment derived predominantly from local sources. Upper parts of beds, especially siltstone and mudstone intervals, commonly are bioturbated. Locally contains small pieces of carbonaceous wood and other organic debris such as leaves. No diagnostic fossil material was recovered in map area, but we observed camel tracks in unnamed middle fork of Palm Wash (located between North and South Forks Palm Wash), immediately south of "flat-topped" hill in Calcite Mine area. Camel tracks are preserved as imprints on top of bedding plane in sandstone. North and west of Calcite Mine area and also west of Arroyo Salada in "Truckhaven Rocks" area, member grades laterally into fine-grained member (QTcf) of the Canebrake Conglomerate. East of Calcite Mine, member also laterally interfingers with strata of the Arroyo Diablo Formation. East of Arroyo Salada to Calcite Mine area, lower member (Tol) could be further subdivided into various subfacies that are indicative of floodplain setting, from channel-confined sands to laterally equivalent, overbank, silt-dominated sediments. Paleocurrent measurements were not collected systematically; however, data collected from tangential cross-stratification and Gilbert-type delta foresets in lower member indicate depositional directions from southeast and east. Age of unit is late to early Pliocene

Arroyo Diablo Formation—Basinward lateral equivalent of the Olla Formation. We include two subunits (Td1 and Td2) in this formation that have sediment sourced from Colorado River. Plant remains and petrified wood are relatively common (Winker, 1987; Remeika and others, 1988), but they are not age diagnostic. No other fossil material was collected in map area. In Fish Creek–Vallecito Creek basin region, magnetostratigraphic data calibrated by fission-track age on air-fall tuff bed constrain age of basal strata of formation to about 4.0 Ma; vertebrate fossils support this age determination (Johnson and others, 1983; Winker, 1987; Cassiliano, 2002; Dorsey and others, 2011). In its type area, age of top of formation is extrapolated to be about 2.8 Ma (Dorsey and others, 2011). In southeastern part of map area, upper part of formation interfingers with lower part of the Borrego Formation, leading to transitional boundary between these two units. On map, contact is arbitrarily positioned to reflect change from predominantly light-pink, fine-grained sandstones of this formation to claystone-dominated strata of the Borrego Formation. Workers generally agree about depositional environment of formation: Dibblee (1954, 1984), Quin and Cronin (1984), Winker (1987), and Dorsey and others (2011) considered that progradation of ancestral Colorado River delta plain into Salton Trough best fits sedimentological characteristics of this widespread formation. Sandstone facies of subunit 1 (Td1) is represented by fining- and thinning-upward cycles, representing point-bar, delta, levee, and floodplain depositional settings, and locally intercalated thin siltstone, mudstone, and claystone intervals, representing lacustrine, marsh, and (or) overbank-swamp deposits. Within map area, lateral transition to thicker mudstone and claystone-dominated strata of subunit 2 (Td2) represent longer term overbank-depositional and (or) lacustrine settings on expansive Colorado River deltaic floodplain. We did not execute systematic study of paleocurrent directions in map area, but we made limited number of paleocurrent determinations from cross-stratification, parting lineations, and ripple-drift lamination; these yielded wide scatter of results, but general trend indicates westward sediment dispersal. Mapped as the following two subunits:

Td2 — **Subunit 2 (upper to lower Pliocene)**—Thick, reddish-brown mudstone and (or) claystone and thin beds of sandstone and siltstone. Claystone beds are typically massive and reddish-brown. Local grayish-green and grayish-blue horizons are also present. Mud cracks are observed at contacts with overlying sandstone and siltstone beds; in addition, irregularly shaped light-gray calcareous nodules are present, which are interpreted as disrupted paleocaliche horizons.

Td1 — **Subunit 1 (upper to lower Pliocene)**—Massive to thick-bedded, pale-pink, concretionary, fine-grained to very fine grained quartzose sandstone and siltstone, interbedded with reddish-brown mudstone and claystone. Distinctive yellowish-gray, pyritic sandstone marker beds of mixed Colorado River and local sources where formation laterally transitions to the Olla Formation, as in Calcite Mine area. Massive to thick-bedded sandstones commonly are found in thinning- and fining-upward cycles that are between about 5–20 m in thickness. In any one cycle, basal beds are generally coarser grained and may contain reworked sediments from local sources, including granitoid conglomerate clasts. Top of individual cycles locally grade into siltstone and claystone. Basal sandstone contacts are sharp, and, in lower parts of beds, rip-up clasts of red-brown mudstone/claystone are found locally. Basal contacts of individual cycles commonly are discordant and indicate local scouring and channel development. Laterally, sandstones are lenticular, and several beds may combine to form thick packets of sandstone strata. Internally, coarse-grained basal parts of individual sandstone beds may contain parallel and convolute lamination and cross-stratification. Upper intervals of finer grained sandstone that grades to siltstone are commonly ripple laminated. Characteristic feature of subunit 1 sandstone is development of irregularly shaped calcareous concretions

BORREGO FORMATION

Borrego Formation—First named by Tarbet and Holman (1944). From its type locality in Borrego Badlands, directly south of Vista del Malpais, described by Dibblee (1954) as "light-gray claystone and interbedded sandstone" containing "lacustrine fauna of minute mollusks, ostracods and rare foraminifera" (Dibblee, 1954). Cassiliano (2002) noted that formation is lateral equivalent of the Arroyo Diablo Formation and Canebrake Conglomerate of his Palm Spring Group, but the Borrego Formation has not been included in the Palm Spring Group. Within map area, formation is informally subdivided into three subunits. Oldest strata assigned to formation in study area crop out in main stem of Arroyo Salada and North Fork Arroyo Salada area, in southeastern part of map area; here, in thick transition zone, beds of Borrego Formation-like lithologies alternate with beds of sandstone-dominated strata that are typical of upper strata of the Arroyo Diablo and (or) the Olla Formations of the Palm Spring Group. West of Palo Verde Wash, upper contact with basal sandstones and conglomerates of the overlying Ocotillo Formation is clearly defined and sharp. However, in badlands west and northwest of Seventeen Palms and east of Palo Verde Wash, upper strata of formation interfinger with thin beds of lower member of the Ocotillo Formation. Formation was interpreted as lacustrine (for example, Dibblee, 1954; Winker, 1987). Transition to basal strata of formation from strata of the Arroyo Diablo Formation was considered by Winker (1987) to reflect lacustrine mudstones and claystones of formation alternating with fluvial strata (thick channel sandstone and reddish-brown overbank mudstone and claystone) typical of the Arroyo Diablo Formation. Age of unit is middle Pleistocene to upper Pliocene, on the basis of stratigraphic position and regional correlations. Mapped as the following three subunits:

Qb3 — **Subunit 3 (middle to early Pleistocene)**—Interbedded lenses of locally derived, fine-grained conglomerate and micaceous sandstone, similar to strata of the overlying Ocotillo Conglomerate

Qb2 — **Subunit 2 (middle to early Pleistocene)**—Distinctive dark- to light-greenish-gray to green claystone marker bed

QTb1 — **Subunit 1 (middle Pleistocene to upper Pliocene)**—Crops out extensively in southern part of map area; consists primarily of pink, yellow, and pale-orange, thin-bedded, fine-grained to very fine-grained sandstone, buff to light-gray siltstone, mudstone, fissile claystone, and minor reddish-brown and green, fissile claystone. Sediment sourced from Colorado River. Mudstone and claystone beds predominate. Sandstones are generally very soft and friable, although some sandstone beds are calcite cemented and locally concretionary. Beds typically appear structureless, but parallel laminations and ripple-drift laminations are present. Bedding is uniform and parallel over multiple kilometers

SPLIT MOUNTAIN FORMATION

Split Mountain Formation—Oldest exposed Cenozoic rocks in map area; nonmarine. Type area is approximately 40 kilometers (km) south in Split Mountain gorge, where Tarbet and Holman (1944) described unit as consisting of red and grayish-green fanglomerates, sandstones, and diorite breccia. Many subsequent workers have studied these rocks, including Dibblee (1954), Woodard (1974), Kerr (1984), Winker (1987), Kerr and Kidwell (1991), Winker and Kidwell (1996), Kerr and Abbott (1996), Abbott and others (2002), and Dorsey and others (2011). Winker and Kidwell (1996, fig. 5) and Dorsey and others (2011) advocated raising formation to group status; however, this has not been done formally and, hence, formation status is retained herein. In map area, formation consists of two interfingering lithofacies (subunits Tsm2 and Tsm1) that, although we do not formally name, can be correlated with stratigraphic units previous workers have identified elsewhere in Borrego Desert region. Dibblee (1954) first correlated formation with rocks in southern Santa Rosa Mountains. Outcrops found in northern part of map area, both in Smoke Tree Canyon and north of Calcite Mine, are correlated (on the basis of field descriptions) with equivalent successions mapped elsewhere along western margin of Salton Trough. Mapped as the following two subunits:

Tsm2 — **Subunit 2 (upper? Miocene)**—Crudely stratified; includes reddish-brown to purplish boulder, cobble, and pebble conglomerates and interfingering laminated sandstone and siltstone lenses. Interpreted as alluvial fanglomerates that are transitional to fluvial-floodplain deposits. Crops out in northeastern part of map area. Interfingers with subunit Tsm1. No diagnostic fossils were collected. Laminations containing leaf imprints and small carbonaceous twigs and branches are present

Tsm1 — **Subunit 1 (upper? Miocene)**—Crudely stratified, grayish-green, purplish, and reddish-brown monomictic and polymictic breccias, chaotic landslide deposits, talus deposits, and coarse-grained fanglomerate debris-flow deposits. Best exposures restricted to northeastern part of map area. Sharp basal contact with paleorelief of underlying, highly fractured to brecciated granodiorite and diorite of Peninsular Ranges batholith (Kp). Upper contact is locally unconformable because of paleodrainage dissection of formation. More generally, transition from formation to the overlying Canebrake Conglomerate is conformable, having 2–10 m transitional zone marked by grayish- to purplish-brown sandstone and (or) debris-flow deposits. No diagnostic fossils have been collected. Coarse-grained breccias and conglomerates are locally sourced from nearby exposures of underlying granodiorite and diorite; much of succession is inferred to be proximal to source, on the basis of genetic interpretations of thick landslide deposits, debris-flow deposits, talus deposits, and fanglomerates. Exposures in upper reaches of Smoke Tree Canyon include basal monomictic breccias resting on highly fractured and (or) brecciated granodiorite and diorite (Kp). Canyon-wall exposures document coarse-grained fanglomerate overlying breccias which are in turn, overlain unconformably by strata of the Canebrake Conglomerate. In northeastern part of map area, series of generally north- to northwest-trending alteration zones have formed in subunit; these hydrothermal alteration zones have irregular margins. Several zones can be traced into underlying brecciated granodiorite (Kp), but none are observed to intrude the overlying Canebrake Conglomerate. Inferred emplacement is via hydrothermal fluids streaming up through fracture network of underlying basement rocks of hanging wall of West Salton Detachment Fault. Locally, purplish- to reddish-brown, patchy hematite coloration is attributed to hydrothermal alteration and mineralization associated with formation of alteration-zone network within subunit. These alteration zones are mapped as dikes

BASEMENT ROCKS

West of Salton Trough, rocks in San Jacinto and Santa Rosa Mountains consist of pre-Mesozoic metasedimentary rocks of greenschist- to amphibolite-grade metamorphism that are intruded by Cretaceous granitic rocks; Eastern Peninsular Ranges mylonite zone (for example, Sharp, 1979; Sylvester and Bonkowski, 1979; Simpson, 1985; Todd and others, 1988) cuts across these rocks. These crystalline basement rocks are mapped, in limited extent, in northern part of map area. No detailed mapping or descriptions were compiled for these rocks; however, their extensive exposures at higher elevations in Santa Rosa Mountains are source of locally derived Pleistocene to Pliocene and Miocene cover strata.

Kp — **Plutonic rocks of Peninsular Ranges batholith (Cretaceous)**—Rocks assigned to Peninsular Ranges batholith (Larsen, 1948; Silver and Chappell, 1987; Morton and Miller 2014) are widely mapped across southern California and in Mexico, as far south as southern tip of Baja California (for example, Sylvester and Bonkowski, 1979; Silver and Chappell, 1987; Morton and Miller 2014). Calc-alkaline granitoid plutons are middle to early Cretaceous (Krummenacher and Doupont, 1975). Average composition is tonalite, but range of compositions from granite to diorite is represented. Within map area, rocks assigned to Peninsular Ranges batholith range from minor bodies of granite and granodiorite to more common bodies of quartz diorite and dark-green hornblende quartz diorite. Minor inclusions of gneiss are present, and several generations of pegmatitic dikes are characteristic of batholith. Outcrops are limited to upper reaches of Smoke Tree Canyon in northwest and in topographically elevated northeastern parts of map area. Where exposed, granitic, granodioritic, and dioritic rocks are generally highly fractured to brecciated, forming base of upper plate of West Salton Detachment Fault

MzPzc — **Cataclastic rocks of Eastern Peninsular Ranges mylonite zone (Mesozoic and Paleozoic)**—East-dipping Eastern Peninsular Ranges mylonite zone in southern California (for example, Sharp, 1966, 1967, 1979; Simpson, 1985) is mostly made up of pervasively sheared Cretaceous granodiorites and tonalities of Peninsular Ranges batholith (mapped as the plutonic rocks of Peninsular Ranges batholith, Kp) and Mesozoic and Paleozoic metasedimentary rocks (for example, marble and quartzite). Age of mylonite zone is Late Cretaceous, on the basis of fission-track and potassium-argon (K-Ar) dating (for example, Dokka and Frost, 1978; Wallace and English, 1982; Dokka, 1984; George and Dokka, 1994). Simpson (1984) described Late Cretaceous-age structural shear indicators that record west-directed thrust slip within mylonite zone. Outcrops are restricted to northwestern part of map area, in upper reaches of Palo Verde Wash and in small window exposure in nearby Smoke Tree Canyon. Predominant rock type is gneiss. A sharp low-angle fault separates footwall mylonite zone rocks from hangingwall comprised of highly fractured and brecciated granodiorite with overlying cover rocks assigned to the Canebrake Conglomerate. Directly above the low-angle fault the hangingwall units are associated with 1- to at least 15-m-thick gouge zone that contains phacoidal structures of granodiorite and (or) diorite, as well as various metamorphic rock types that include gneiss, amphibolite, and marble. This sharp fault, which defines top of Eastern Peninsular Ranges mylonite zone, was first interpreted as Cretaceous-age thrust fault (Sharp, 1967). However, Wallace (1982) described this fault as Miocene-age detachment fault; fault also was included as part of West Salton Detachment System by Axen and Fletcher (1998) and we have adopted this correlation herein. Similar field relations between Eastern Peninsular Ranges mylonite zone and Pliocene-Miocene-age detachment faulting was reported (for example, Schultejahn, 1984; Frost and others, 1996a, b; Shirvell and others, 2009; Steely and others, 2009; Dorsey and others, 2011) in Yaqui Ridge area, southwest of Borrego Springs along southwestern margin of Salton Trough; these mylonite zone–fault relations are interpreted herein as being dextrally displaced equivalent of detachment fault in southern Santa Rosa Mountains map area

EXPLANATION OF MAP SYMBOLS

Contact—Solid where location is accurate; dashed where location is approximate; dotted where location is concealed; queried where identity or existence is questionable

Internal contact—Internal unconformities within unit formed by coeval deformation and erosional dissection during sedimentation; light purple highlight included on map for clarity

Faults—Solid where location is accurate; long-dashed where location is approximate; short-dashed where location is inferred; dotted where location is concealed; queried where identity or existence is questionable

Fault—Paired arrows indicate direction of relative offset; single arrow indicates direction and amount of fault-plane dip. For normal-slip faults, U indicates upthrown side; D indicates downthrown side. In cross section, A indicates movement away from observer; T indicates movement toward observer

Thrust fault—Sawteeth on upper plate

Folds—Solid where location is accurate; dashed where location is approximate; dotted where location is concealed; queried where identity or existence is questionable. Showing direction of plunge where known

Anticline

Overturned anticline

Syncline

Overturned syncline

Monocline—Showing anticlinal and synclinal flexures

Mineralized alteration zone

Fracture—Joint or minor fault set that contains calcite veins

Shear zone

Bedding form line and (or) marker bed—Dotted where projected above surface

Topographic scarp—Hachures at base of scarp point downslope; no locational accuracy

PLANAR POINT FEATURES

Strike and dip of bedding—Showing dip where known

Horizontal

Inclined

Vertical

Overturned

Strike and dip of metamorphic foliation

Dome

Basin

INTRODUCTION

This investigation delineates the geologic framework of an area of 75 square kilometers (km^2) located west of the Salton Sea in southern California (fig. 1, on sheet 1). The study area encompasses the south flank of the Santa Rosa Mountains and the eastern part of the Borrego Badlands (sheet 1). In this study area, regionally important stratigraphic and structural elements collectively inform the late Cenozoic geologic evolution of the Anza-Borrego sector of the Salton Trough province. Critical stratigraphic and structural elements in the map area include the following:

1. The well exposed sequence of late Cenozoic, nonmarine sedimentary rocks that filled the Anza-Borrego subbasin (fig. 1) of the Salton Trough;
2. A tectonic boundary that—in the southern Santa Rosa Mountains—separates the sedimentary strata from underlying crystalline rocks of Peninsular Ranges type. This tectonic boundary, named the West Salton Detachment Fault System by Axen and Fletcher (1998), is projected to underlie all late Cenozoic sedimentary strata in the Anza-Borrego subbasin of the Salton Trough;
3. A variety of transpressional, transtensional, and strike-slip structures that have deformed the late Cenozoic sedimentary strata and collectively guided syntectonic and posttectonic depositional events within the Anza-Borrego subbasin of the Salton Trough; and
4. The southeasternmost surface expression of the Clark Fault, a major strand of the dextral San Jacinto Fault Zone.

Geologic mapping and analysis for this investigation focused on clarifying geologic relations among these four stratigraphic and structural aspects in the map area.

GEOLOGIC SETTING

The upper Cenozoic sedimentary basin fill of the Salton Trough and contiguous Anza-Borrego subbasin (fig. 1) is best exposed in the area encompassed by the subbasin. Dextral displacements on the Clark Fault strand of the San Jacinto Fault Zone have formed a structural reentrant in the northern part of the Anza-Borrego subbasin, defined by Clark Valley. The crystalline basement of the Santa Rosa Mountains form the northeastern margin to Clark Valley, with the Santa Rosa Mountains displaced to the southeast by dextral slip on the Clark Fault. Quaternary transpressional deformation along and between the various strands of the San Jacinto Fault Zone that dissect the Anza-Borrego subbasin has partially inverted the basin-fill strata. The depositional history of this late Miocene to Quaternary basin-fill sequence records the inception and development of the Salton Trough in response to the initiation of low-angle normal-fault slip on the West Salton Detachment Fault System (Axen and Fletcher, 1998) and subsequent transition to dextral slip deformation associated with the establishment of the San Jacinto Fault Zone (Kirby and others, 2006; Janecke and others, 2010; Dorsey and others, 2011).

STRATIGRAPHIC FRAMEWORK ADOPTED FOR THIS REPORT

In a pioneering study, Dibblee (1954) prepared the first regional geologic map of the Salton Trough, including parts of the Borrego Badlands and southern Santa Rosa Mountains. Dibblee's work set up the regional framework for stratigraphic nomenclature. The stratigraphic formation and member names adopted in the map area for the extensively outcropping late Neogene and Quaternary basin-fill strata are generally correlated with and follow the nomenclature established by previous workers in the Salton Trough region, especially Woodring (1932), Tarbet and Holman (1944), Dibblee (1954, 1984), Winker (1987), and Cassiliano (2002).

In this investigation, we group map units as follows: (1) basement units (pre-Cenozoic); (2) cover rocks (upper Cenozoic to late Neogene and Quaternary); and (3) surficial deposits (late Pleistocene to Holocene). The map-unit descriptions and correlations are included on sheet 2, as well as a facies-correlation diagram (refer fig. 7) that highlights the complexity of the interfingering relations associated with the basin-margin setting of the map area. New informal member subdivisions are used to provide stratigraphic mapping and correlation details within each of the cover rock units, as well as to better constrain structural relations. Broadly, stratigraphic units are assigned to one of three source affinities, (1) proximal sediment sources; (2) distal basin-fill units primarily sourced from the Colorado River system; and (3) units that have mixed-source provenance, marking the transition from the proximal sources to the basin-margin sources to the more distal basin-fill sources. Further detail is provided in the Description of Map Units (sheet 2). Because of the limited geographic extent of this study, no revised formalized stratigraphic subdivisions are included here.

STRUCTURAL GEOLOGY

Within the map area, the termination of the Clark Fault surface trace is accompanied by the immense structural complexity seen in the late Miocene to Pleistocene, nonmarine sedimentary cover strata that crop out in the southern Santa Rosa Mountains and the contiguous Borrego Badlands. The stratigraphic relations and associated structural deformation are fundamentally related to two interacting structures:

1. Clark Fault (mapped by some others as the Clark strand of the San Jacinto Fault Zone; however, we use the name "Clark Fault" herein)—The dextral strike-slip Clark Fault traverses the map area diagonally from northwest to southeast (figs. 2, 3); its surface-trace termination tip is in the center of the map area. We infer that the fault continues as a blind (?) structure concealed beneath cover strata to the southeast. This interpretation requires that the dextral Clark Fault has undergone a transpressive left bend and (or) step-over in upper crustal basement at depth beneath the cover strata (for example, Peterson and others, 1991). This structural geometry, in turn, drives multiple shallow thrust faults, as well as en echelon, sigmoidal to anastomosing patterns of fold axial traces that are found within cover rocks to the south and west (figs. 2, 3, 5, 6). These structures reflect the dextral "drag" and oblique thrust-slip motion that is deforming the structurally decoupled cover strata mapped around the southern margin of the Santa Rosa Mountains and into the eastern Borrego Badlands.
2. West Salton Detachment Fault System—Locally, in the study area, reactivated by Quaternary northward thrust-fault motion. Various workers have recognized that well-known late Cenozoic sedimentary strata in the greater Borrego Valley region, accumulated on the hanging-wall of a regionally extensive low-angle normal-slip fault—the West Salton Detachment (for example, see Remeika, 1995; Axen and Fletcher, 1998; Kirby and others, 2006; Janecke and others, 2010; Dorsey and others, 2011).

In the southern Santa Rosa Mountains, northeast of Borrego Valley, Sharp (1979) recognized that sedimentary rocks high in the mountains were separated from crystalline rocks of Peninsular Ranges type by low- to moderate-angle faults. Sharp reasoned that the sedimentary rocks had been dropped from a higher structural level, although he did not explore the implications of this conclusion. Figure 5 of Axen and Fletcher (1998, fig. 5) incorporated Sharp's (1979) mapping into their projection of the West Salton Detachment Fault System into the southern Santa Rosa Mountains and beyond, including the fault Sharp (1979) had mapped between basement rocks and sedimentary cover strata.

More recently, structural and stratigraphic relations in the southern Santa Rosa Mountains were investigated by the U.S. Geological Survey (Cox and others, 2002; King and others, 2002; Matti and others, 2002, 2006). These investigators focused on how hanging-wall rocks in the southern Santa Rosa Mountains originally deposited near sea level could now be situated at elevations as great as 600 meters (m) above sea level. They invoked Quaternary contractional uplift of the southern Santa Rosa Mountains was interpreted as a mechanism for elevating sea-level hanging-wall rocks to their current anomalous elevations. However, Dorsey and Langenheim (2015) dismissed this interpretation and proposed that the southern Santa Rosa Mountains and their sedimentary cover strata were uplifted by crustal tilting (up on the west) triggered by normal dip-slip displacement on the Santa Rosa Fault.

Pettinga (1989, 1991) proposed that the crystalline core of the southern Santa Rosa Mountains appeared to have "snowplowed" the cover strata that flank the Santa Rosa Mountains basement rocks—an idea that invokes contractional convergence and crucially the basement-cover decoupling between the two crustal elements. Our mapping elaborates and refines that idea by using outcrop observations and deformation styles in the late Cenozoic cover strata to show that north and east of the Clark Fault, the cover strata have been emplaced to the north-northwest over crystalline basement rocks of the Santa Rosa Mountains. Convergence between the two crustal elements occurred by Quaternary reactivation and slip-reversal of a segment of the West Salton Detachment Fault. These broad, anticlinally arched and internally complexly deformed late Cenozoic cover strata have been decoupled from underlying basement rocks and the shallowly southeastward dipping, reactivated detachment fault, and they have been driven northward by transpressive dextral shear (fig. 3).

STRUCTURAL DOMAINS

Thrust-slip reactivation of a segment of the inherited West Salton Detachment Fault System has driven progressive structural inversion along the northeastern margin of the Anza-Borrego subbasin. We document important new insights into the effects that localized reactivation and slip reversal of the detachment fault have had on the contrasting deformation styles and geometries associated with the coarse, clastic basin-margin deposits versus those of the more distal, fine-grained basin-fill units (figs. 3, 5, 6). Spatial differences in structural styles and associated kinematics in the map area are best represented by the following four structurally distinct domains (fig. 2, on sheet 1):

- Domain 1—The lower plate (or footwall) of the detachment fault, which includes basement rocks assigned to the Eastern Peninsular Ranges mylonite zone and the Southern California batholith;
- Domain 2—The western part of the overthrust sheet, which is a structurally lower elevation block that has been subjected to a moderate degree of structural inversion, in which (a) cover strata have been affected by coeval deformation, sedimentation, and dissection and (b) the associated underlying basement of fractured to brecciated granites (assigned to the Southern California batholith) are exposed in the upper plate (hanging wall), where cover strata are deeply dissected;
- Domain 3—The eastern part of the overthrust sheet, which consists of cover strata and units in the upper plate (hanging wall) of the detachment fault that form a structurally and topographically elevated block, which has been subjected to a high degree of structural inversion, with deeply dissected strata arched upward, that is characterized by a network of east-west-oriented strike-slip faults and also accommodating north-south-directed contractional deformation (fig. 6);
- Domain 4—An area typified by complex en echelon folding over a series of shallow décollements within the cover strata (figs. 3, 5).

The structural domains are generally separated by major structural elements (fig. 2): (1) the surface trace of the dextral strike-slip Clark Fault broadly separates domains 1 and 2 from domain 4; (2) the reactivated detachment fault separates domain 1 from domain 2; and (3) the sinistral Truckhaven Fault separates domains 2 and 3 (fig. 4). The boundary between domains 3 and 4 is less well defined because it marks a transitional zone that separates the contrasting deformation styles of margin-proximal and more distal sedimentary units. This domain boundary also coincides broadly with the projected subsurface location of the left bend and (or) step-over zone in the Clark Fault, beneath the decoupled cover strata; the boundary may be reflected indirectly in surface exposures by an associated zone of complex shearing east of Arroyo Salada wash, south of Country Road S22, also known as the Borrego-Salton Seaway.

Within domains 2 and 3—north and east of the Clark Fault—the late Miocene to Pleistocene basin-margin clastic cover strata are deformed into an open, gently southward-plunging anticline (fig. 2; domains 2 and 3), which was formed by northward-directed thrust-slip emplacement of the cover strata onto the flank of the Santa Rosa Mountains along the shallowly southeastward dipping, reactivated detachment fault. In the core of this fold, the north-northeast-striking, sinistral Truckhaven Fault represents a tear fault in the thrust sheet between the two structural domains (fig. 4). The Truckhaven Fault has an apparent antithetic relation to the Clark Fault, but the Truckhaven Fault is inferred to be confined to near surface structural depths, affecting only the thrust sheet above the reactivated detachment fault.

Domain 3 forms the elevated, uniformly dipping east limb of the broad, gently southward plunging, open anticlinal fold of the domain 2 and 3 thrust sheet that lies above the reactivated detachment fault. Domain 3 is characterized by an intricate network of east-west-oriented dextral-slip faults grouped within the Calcite Mine Shear Zone (fig. 6), which, in combination with bedding shears, have accommodated the complex deformation of interfingering units of the Palm Spring Group and the underlying Split Mountain Formation (fig. 6). The northern frontal margin of the domain 3 thrust sheet—structurally positioned above the reactivated detachment fault—is locally folded and faulted along an east-west-aligned axis that extends from west of "Pyramid Peak" to east of "East Peak". This fold is cored by upper plate (with respect to the detachment fault) basement rocks and the basal cover strata assigned to the Split Mountain Formation (figs. 3, 6).

Domain 2 forms the west limb of the broad, gently southward plunging, open anticlinal fold of the domain 2 and 3 thrust sheet that lies above the reactivated detachment fault. In this west limb, structural complexity decreases upward through the stratigraphic sequence. Numerous local (internal) unconformities are present within the Canebrake Conglomerate, indicating that deformation, dissection, and deposition were occurring simultaneously (see cross section C–C', on sheet 1). The Canebrake Conglomerate, which is sourced from the elevated south flank of the Santa Rosa Mountains (domain 1) and also "cannibalized" from deforming strata of the Canebrake Formation, was being contemporaneously thrust back up into the "throat" of the source area. Footwall basement rocks of the Santa Rosa Mountains were "snowplowed" beneath the arching, deforming, hanging-wall cover strata along the thrust-slip-reactivated West Salton Detachment Fault. This contractional style of deformation has substantially contributed to the structural and stratigraphic complexity along the basin margin (Pettinga, 1989, 1991).

In the eastern part of the Borrego Badlands, south and west of the surface-termination tip of the Clark Fault (figs. 2, 5), en echelon to sigmoidal and anastomosing patterns of axial traces of folds were generated by dextral rotational drag and oblique-thrust slip as the deforming cover strata became decoupled from the underlying, reactivated West Salton Detachment Fault. Deformation here is dominated by complex, asymmetric, en echelon folding above numerous shallow, mainly northward dipping décollements that developed within the cover strata, primarily in the lacustrine facies of the Pliocene to Pleistocene Borrego Formation. Within this succession, short- to medium-wavelength (tens to thousands of meters), thrust-propagated and nested folds reflect numerous shallow, vertically stacked, stratigraphically confined décollements. In the southwestern part of the map area, the opposite-facing North and South Short Wash Anticlines (figs. 2 [on sheet 1], 5) are linked in map view via the complexly stranded, dextral Fault Wash Transfer Fault Zone. This fault zone terminates at shallow depth on the unusually stepped décollement structure of the Borrego Thrust Fault Zone (cross section E–E'; fig. 5). The Borrego Thrust Fault Zone is accommodating a clockwise-directional structural rotation. Within domain 4, the various styles of deformation are driven by the shortening and structural rotations induced by the dextral Clark Fault at depth, which is partly concealed by the deforming cover strata (figs. 3 and 5), as well as the pervasive contractional deformation of the detached cover strata that is driven by thrust-slip reactivation of the West Salton Detachment Fault.

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