Tectonic Transpression and Basement-Controlled Deformation in San Andreas Fault Zone, Salton Trough, California

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Abstract The San Andreas fault zone in the Salton trough is characterized by subparallel, high-angle faults, en echelon folds, and systematically arranged arrays of reverse and normal faults which are typical of major wrench faults elsewhere in the world. Detailed field mapping in the Mecca Hills shows that the fault zone is delineated by two northeast-striking high-angle faults which subdivide pre-Cenozoic crystalline and schistose basement and overlying late Cenozoic and Quaternary nonmarine sedimentary rocks into three structural domains: (1) a high-standing, relatively undeformed block northeast of the fault zone; (2) a 1.5 km-wide zone of folded sedimentary rocks between the two faults; and (3) a sparsely exposed, deeply downfaulted block on the southwest. Locally the two faults branch upward and flatten abruptly outward into low-angle thrusts which carry thrust slices and gravity slides of sedimentary rocks from the central block short distances on to the adjacent blocks. Between the two faults the sedimentary succession is folded into broad west-northwest-trending open folds which tighten and are overturned and truncated against the faults. Where exposed in the fault zone the basement sedimentary rock contact is a buttress unconformity which also is folded and overturned locally. Field observations reveal that the basement in the core of the fold is fractured and sheared perversely, indicating that the mechanism of basement deformation was one of cataclastic flow by piecemeal slip on the closely spaced fracture and shear planes, whereas the folding of the overlying sedimentary rocks was largely a passive consequence of deformation at the basement level. Although horizontal shear strain predominated, local vertical uplift of the basement occurred as a result of compression between two convergently and laterally slipping rigid crustal blocks.

INTRODUCTION

En-echelon anticlines associated with major wrench faults constitute the structural style of some of the most important and productive oil and gas fields in California, as well as other parts of the world (Harding, 1973, 1974, 1976). Together with related subsidiary reverse faults and low-angle thrusts, these folds are evidences of a shortening component of strain associated with the more dominant shear component. Crowell (1974) has shown that these structures form typically in the vicinity of bent or braided parts of wrench faults where the slip of the two crustal blocks is simultaneously lateral and convergent. Harland (1971) proposed the term "transpression" for the concept of lateral and convergent slip along wrench faults.

Recent clay-model studies of the geometry and kinematic history of the assemblages of structures formed in transpression (Wilcox et al., 1973), show that en echelon folds typically form at low angles to the main trace of a wrench fault, and that the geometry of the fold axial traces depends on the sense of horizontal shear strain (Fig. 1). Although these model studies, together with those of Hafner (1951) and Sanford (1959) on dip-slip faults, give bases for understanding the origin of upthrusts and associated folds in thick
sequences of layered sedimentary rocks, little attention has been focused on the nature and mechanism of deformation at the basement level in wrench-fault zones, or on the effect of basement deformation on the overlying sedimentary succession. This lack of attention has led to erroneous assumptions and questionable interpretations. For example, it is common to find in the literature structure sections across wrench faults which imply a moderately to tightly folded crystalline basement-sedimentary rock interface that is concentric to the observed folds in the overlying sedimentary rocks, as if the basement deformed plastically. However, palinspastic reconstructions of the depth to basement in most studies show that the basement was relatively shallow during deformation—too shallow to have deformed ductily by plastic flow and recrystallization. As Prucha et al (1965) showed in upthrust areas and from experimental studies in rock deformation, it is clear that basement composed of rock types such as gneiss and massive plutonic rocks cannot be folded simply, but must deform by pervasive brittle fracturing leading to cataclastic flow at the relatively shallow depths inferred from the palinspastic reconstructions.

In this paper we document the geometry and tectonics of structures in an unusually well-exposed part of the southern San Andreas fault zone where the mechanism of basement deformation is displayed clearly and can be related to folding of the overlying sedimentary cover. Whereas Crowell (1974) provided models for wrench-fault tectonics on a regional scale, this investigation provides models on the scale of an oil field for the geometry and origin of subsidiary folds and faults which form as a result of transpression and which, in other areas, have been found to be important traps for hydrocarbons.

**Tectonic Framework**

The Coachella and Imperial Valleys (Fig. 2) comprise an elongated structural depression known as the Salton trough which is considered to be the landward extension of the Gulf of California. The trough is believed to be a complex rift formed by crustal spreading at the northern extension of the East Pacific Rise; the plate motion is thought to be transformed to the San Andreas fault near the south end of the Salton Sea, south of which the fault has not been traced with confidence (Carey, 1958; Hamilton, 1961; Allison, 1964; Biehler et al, 1964; Hamilton and Myers, 1966; Elders et al, 1972; Sharp, 1972).

Salton trough is bounded by northwest-trending mountains which are underlain on the northeast by plutonic, metamorphic, and volcanic rocks ranging in age from Precambrian to late Tertiary (Table 1). Massive plutonic rocks of the southern California batholith of middle Cretaceous age and prebatholith metamorphic rocks are exposed in the Santa Rosa Mountains and other ranges southwest of the trough.

Gravity studies in Coachella Valley indicate that this part of the trough is a half-graben tilted northeastward with the deepest part (4,000 to 5,000 m deep) against the San Andreas fault zone adjacent to the Meeca Hills (Biehler, 1964).

The broad outlines of the stratigraphy of Cenozoic rocks filling the trough have been summarized by Tarbet and Holman (1944), Tarbet (1951), and Dibblee (1954), but the details are not well known because obscure well records cannot be correlated confidently with sparse exposures along the trough margins (Dibblee, 1954; Muffler and Doe, 1968). In general, the distribution of sedimentary facies is asymmetric as shown in Figure 3. Preceding and following a marine incursion in the Pliocene, represented by shale and mudstone of the Imperial Formation, deposition was characterized by intermittent and interfingering alluvial-fan, flood-plain, and lacustrine sediments derived from the surrounding mountains and the Colorado River (Merriam and Bandy, 1965). Volcanic rocks of late Cenozoic age crop out sparingly around the edges of the trough and are intercalated with the sedimentary succession (Fig. 3).

The San Andreas fault zone is the northeasternmost of a number of major northwest-
Tectonic Transpression In San Andreas Fault Zone

FIG. 2—Index map showing principal tectonic and geographic features of Coachella and Imperial Valleys. Together, these two valleys and their tectonic elements comprise Salton trough. Stippled areas are underlain by pre-Cenozoic crystalline and schistose basement rocks.

trending faults of the San Andreas fault system (Fig. 2) which transect the Salton trough and trend more westerly than the axis and borders of the trough (Sharp, 1972). The San Andreas fault zone is exposed discontinuously as far south as the Durmid area in the Indio Hills and the Mecca Hills; between these exposed areas, however, the fault can be traced by discontinuous fault scarps in Quaternary alluvium.

Detailed mapping in the Indio Hills (Dibblee, 1954; Popenoe, 1959; Stotts, 1965), the Mecca Hills (Dibblee, 1954; Hays, 1957; Ware, 1958; Sylvester and Smith, 1975; and this paper), and the Durmid area (Dibblee, 1954; Babcock, 1974) shows that the San Andreas fault zone is a relatively narrow, northwest-trending zone of anastomosing high-angle faults and associated west-northwest-trending, locally overturned en-echelon folds. The axial traces of the folds are either straight or curvilinear in flattened S patterns, indicative of right slip on the wrench fault. Subsidiary high-angle faults have arcuate traces trending from nearly north a few kilometers northeast of the zone, to northwest within the zone itself. Their geometric relation to the main trace of the San Andreas fault corresponds to the orientation of the synthetic set of Riedel shears (in the terminology of Tchalenko and Ambraseys, 1970) characteristic of a wrench-fault system (Fig. 1).

The Mecca Hills, on the northeast margin of the Salton trough (Fig. 2), consist of pre-Cenozoic crystalline basement rocks overlain by late Cenozoic nonmarine sedimentary rocks. The San Andreas–Skeleton Canyon fault and the Painted
Canyon fault subdivide the Mecca Hills into two structurally distinct domains or blocks which, for the purposes of this study, are termed the platform block and the central block (Fig. 6). A third domain, the basin block, is inferred from gravity data (Bichler, 1964) beneath a thick cover of aluvium southwest of the San Andreas fault. Each block is distinguished by marked differences in deformation style, lithostatigraphy, and stratigraphic thicknesses of sedimentary cover (Table 2). Detailed field investigations were limited to the central part of the area (Fig. 4) where the structural relief is greatest. The structures of each block are discussed in the following sections. Structures related to the major faults are considered in the discussion of the central block.

The only documented historic fault movement in the Mecca Hills was associated with the Borrego Mountain earthquake of April 8, 1968, which had a Richter magnitude of 6.4 (Allen et al., 1968; Allen and Nordquist, 1972). Whereas the primary displacements took place along the Coyote Creek fault on the southwest side of Salton trough (Fig. 2), minor right-slip (from 1 to 2 cm) or creep took place at about the same time on other faults in the Salton trough, including the San Andreas fault in the Mecca Hills. Seismologists concluded that these minor displacements were triggered dynamically by the Borrego Mountain earthquake (Allen et al., 1968, 1972). This was the first time such a triggering phenomenon was demonstrated convincingly.

**LITHOLOGY**

**Basement Rocks**

Banded migmatitic gneiss and anorthosite and related rocks of Precambrian age, Mesozoic granitic rocks, and Orocopia Schist (Table 2) are ex-

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**TABLE 1. ROCK TYPES AND STRUCTURES OF BASEMENT ROCKS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Lithology</th>
<th>Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cottonwood Granite</td>
<td>Porphyritic quartz monzonite</td>
<td>Plutonic intrusion into batholithic basement complex</td>
</tr>
<tr>
<td>Orocopia Schist</td>
<td>Schist, light greenish-gray to black, composed chiefly of chlorite-albite-quartz, quartz-biotite-muscovite-albite, muscovite-actinolite; some quartzite; cut by numerous veins of massive white quartz, cut locally by diabase and rhyolite</td>
<td>Broad east-west trending anticline arch with lesser folds with amplitudes up to 20 m</td>
</tr>
<tr>
<td>Prebatholithic Complex</td>
<td>Hornblende-biotite gneiss, chiefly, dark greenish-gray; foliated locally by diabase, anorthosite, gabbro, syenite, and dikes of granite, pegmatite, diabase, and felsite (Crowell and Walker, 1962)</td>
<td>Disharmonic flow folds; shear fractures; low- and high-angle faults which do not extend into the overlying sedimentary rocks</td>
</tr>
</tbody>
</table>

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**TABLE 2. LITHOSTRATIGRAPHIC AND STRUCTURAL CONTRASTS AMONG THREE STRUCTURAL BLOCKS OF MECCA HILLS**

<table>
<thead>
<tr>
<th>Basin Block</th>
<th>Central Block</th>
<th>Platform Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Cenozoic Basement Rocks</td>
<td>Basement-sedimentary rock surface steeply tilted to southwest</td>
<td>Basement-sedimentary rock surface gently inclined to southwest</td>
</tr>
<tr>
<td>Not exposed</td>
<td>Geodes and granite, highly sheared, of Chuckwalla Complex</td>
<td>Geodesic and plutonic rocks of Chuckwalla Complex, moderately sheared to unsheared; Orocopia Schist</td>
</tr>
<tr>
<td>Alluvium</td>
<td>Arkose and conglomeratic arkose</td>
<td>Arkose, conglomeratic, and conglomerate</td>
</tr>
<tr>
<td>Thickness: 3,000-5,000 m (12,000-15,000 ft)</td>
<td>Thicker stratigraphic sequence than in eastern block (approximately 1,750 m or 5,000 ft)</td>
<td>Relatively thin stratigraphic sequence (~750 m or ~2,000 ft)</td>
</tr>
<tr>
<td>Structure of sedimentary rocks beneath alluvial cover is not known</td>
<td>Broad open folds, locally reversed, and overturned, with axes oblique to traces of major faults</td>
<td>Virtually unfolded except for minor drag folds with axes slightly oblique to fault trends</td>
</tr>
<tr>
<td>Steep northwest-trending normal faults</td>
<td>Steep to gently inclined northwest-trending normal faults</td>
<td></td>
</tr>
</tbody>
</table>

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FIG. 3—Time-stratigraphic diagram for Salton trough. Presence of marine sedimentary sequence of left side of diagram (Imperial Formation) reflects asymmetry of sedimentation in Imperial Valley. All formations except Imperial Formation are nonmarine. Adapted from Abbott (1968).
FIG. 4—Geologic map of central Mecca Hills. AA', BB', CC' are locations of cross sections shown in Figure 5.
FIG. 5—Structural cross sections of central Mecca Hills. For locations see Figure 4.
posed sparingly in the Mecca Hills where deep canyons have cut through the overlying sedimentary sequence (Figs. 4, 5). Felsite dikes cut the gneiss in Painted Canyon at the Painted Canyon fault; they have been dated at 24 m.y. by K-Ar methods (G. Edwards, personal commun., 1967) and represent an early Miocene plutonic-volcanic belt that is widespread in southern California and southwestern Arizona (Olmsted, 1966; Miller and Morton, 1974; Dillon, 1975a). The age and relation of the Orocopia Schist to other basement rock types are not well known, although the schist is considered to have been metamorphosed in late Mesozoic time (Ehlig, 1968). In the nearby Orocopia and Chocolate Mountains, the Orocopia Schist is overthrusted by the Precambrian gneissic complex (Crowell, 1962, 1975; Dillon, 1975b; Dillon and Hazel, 1975); in the Mecca Hills these two rock units are separated by the high-angle Platform fault.

Sedimentary Rocks

The basement rocks are overlain by nonmarine late Cenozoic and Quaternary sedimentary rocks representing alluvial-fan, braided-stream, and lacustrine environments of deposition (Table 3). Stratigraphic thicknesses, age relations, and correlation of various lithologic units along strike and across faults are tenuous because of numerous diastems, abrupt facies changes, and the lack of fossils and distinctive marker beds. However, the gross nature of the sequence records a history of nonmarine deposition near an active basin margin. This is illustrated especially in Painted Canyon by the lowermost unit of the sequence, the Mecca Formation, which thickens abruptly and coarsens markedly across the Painted Canyon fault (Fig. 5). The strata are comprised chiefly of coarse, locally derived, torrentially deposited detritus of gneiss, Orocopia Schist, and granite. The Mecca Formation lies nonconformably on basement northeast of the fault and in buttress unconformity southwest of it. The contact is not exposed for any great distance laterally from Painted Canyon, precluding a more confident reconstruction of the depositional-basin framework.

The Palm Spring Formation (Table 3) appears to mark an abrupt change in provenance from that of the older Mecca Formation, in that strata in the central Mecca Hills are comprised almost entirely of granitic detritus; Orocopia Schist detritus is predominant in the eastern Mecca Hills near the Orocopia Mountains. The Palm Spring Formation appears to record spreading of the central and distal parts of alluvial fans from the Little San Bernardino Mountains on the northeast which are underlain almost entirely by Mesozoic granitic plutons, and from the Orocopia Mountains on the east. Like the Mecca Formation, the Palm Spring Formation thickens abruptly southwest of the Painted Canyon fault (Fig. 5)
and is progressively finer grained southwestward toward the axis of the Salton trough. Numerous diastems within the formation southwest of the Painted Canyon fault probably reflect Pliocene-Pleistocene episodes of folding and faulting along the trough margin.

The Canebrake-Ocotillo conglomerates range in age from Pleocene to recent (Table 3) and are the coarse alluvial-fan facies of the Palm Spring Formation (Dibblee, 1954).

**Structure**

**Platform Block**

The platform block is a discrete structural domain between the Painted Canyon fault and the front of the Little San Bernardino Mountains. It is a pediment with a moderately incised planate erosion surface cut upon gneiss, granite, and Orocopa Schist; the erosion surface dips about 10° to the southwest and is thinly veneered with fluvial strata of the Mecca, Palm Spring, and Canebrake-Ocotillo Formations.

The basement rocks in the platform block are relatively massive and unfractured in contrast to the pervasively fractured and sheared exposures in the central block that are described below. The gneiss is characterized by disharmonic flow folds. Low to high-angle faults lacking gouge locally cut the basement, but they do not extend upward into the overlying sedimentary strata.

The sedimentary strata are undeformed except where they are dragfolded adjacent to several northwest-trending faults which break the pediment into small horsts and grabens (Figs. 4, 5). The faults are generally planar and dip from 30 to 90° with gouge zones ranging from a few centimeters to as much as a meter in width. The drag folds in relatively competent beds of arkose and conglomerate are gentle open structures, whereas in claystone and siltstone, they are smaller, tighter, and moderately overturned (Fig. 7). The synclines in the downfaulted blocks are more open than the corresponding anticlines. Axes of the drag folds are inclined gently and, together with gently inclined slickensides on fault surfaces, indicate a complex history of oblique displacement of the fault blocks.

The Platform fault is a major feature of the platform block, because it separates gneiss and related Precambrian basement rocks from the Orocopia Schist (Fig. 8). The overlying sedimentary strata also are dissimilar across the fault, but their relative position in the stratigraphic succession could not be determined with confidence, so that the sense and amount of displacement could not

![Diagram](https://example.com/diagram.png)

**Fig. 7**—Geometry of Platform fault 1 km northwest of intersection with Eagle Canyon fault. a, Diagrammatic sketch of east wall of canyon. Drag folding is tighter in footwall than in hanging wall. Detail of rectangular area is shown in b, thin-beded sequence of siltstone and claystone (dashed) is dragfolded adjacent to fault and bedding-plane fault in footwall block superposes some beds so that section is dilated locally.
be determined. Nearly horizontal slickensides in the fault plane show that strike-slip displacement occurred most recently.

Central Block

The central block is a structural domain from 1 to 3 km wide between the Painted Canyon fault and the Skeleton Canyon–San Andreas fault zone (Figs. 3-5). It is characterized by broad folds, most of whose axial traces trend west-northwest, oblique to the bounding faults. Adjacent to the faults, the folds are appressed, locally overturned, and in some places truncated by faults. The geometry and structural style of this domain is similar to those documented in proximity to other wrench faults in the Salton trough (Dibblee, 1954; Popenoe, 1959; Stotts, 1965; Sharp and Clark, 1972; Babcock, 1974) and elsewhere (Wilcox et al., 1973).

Basement of gneiss and granite is exposed only along the Painted Canyon fault in Painted Canyon (Figs. 4, 5). The contact between the basement and the Mecca Formation is a buttress unconformity. The angle between the strata and the erosion surface on the basement is about 15°. Locally the contact between the Mecca and Palm Spring Formations is a minor dip-slip fault.

Folds—The Mecca and Palm Spring Formations are folded into several broad major west-northwest-trending folds. Mecca anticline, with a core of highly fractured and sheared basement, is flanked on the south by the Skeleton Canyon syncline and on the north by the Mecca syncline (Figs. 4, 5). Mecca anticline plunges about 15° west-northwestward, so that its structurally deepest exposures are at its northeastern end adjacent to the Painted Canyon fault in Painted Canyon where the anticline is breached to the basement. The north flank of Mecca anticline is folded into a series of smaller folds which are overturned locally to the north-northwest and are truncated by the fault (Figs. 4, 5, 9). Skeleton Canyon syncline is a broad open fold whose axial trace is approximately parallel with the Skeleton Canyon–San Andreas faults. Between the two faults, about 1 km northwest of the mouth of Painted Canyon, two asymmetric anticlines with an intervening syncline are exposed with axial traces subparallel with that of Mecca anticline. They are overturned to the south-southwest.

The tectonic relation of the folded sedimentary sequence and the basement is visible northwest of Painted Canyon adjacent to the Painted Canyon fault where Mecca anticline plunges 30° west-northwest. There the gneissic and granite basement core is fractured and sheared so closely that it has been reduced to a granulated mass of rock fragments ranging typically from 0.5 to 5 cm in diameter. The degree of fracturing increases toward the fault plane until, at the fault itself, the basement is pulverized and gouged; but even in these highly deformed exposures, vestiges of migmatic banding still are preserved in the gneiss, showing that the internal disruption is slight but pervasive. However, the overlying sedimentary strata are sheared only adjacent to the fault plant itself, and the basement–sedimentary rock contact is not disrupted, that is, it has not functioned as a plane of detachment. The relations clearly show that the basement rocks deformed cataclasically by piecemeal slip along fractures and shear planes, whereas the apparently more pliable sedimentary strata merely deformed passively as a consequence of deformation at the basement level, analogous to the draping of a pliable material over a constrained and deformed mass of buck-shot (Fig. 10). From these observations we extrapolate and postulate that the large-scale folding of strata elsewhere within the central block reflects cataclastic deformation of basement within the entire San Andreas fault zone, an interpretation which is discussed more fully in a following section.

On a smaller scale, folding is accomplished within the sedimentary strata by buckling and
bedding-plane slip, particularly in oversteepened flanks of the major anticlines and in the cores of synclines. Such relatively minor structures die out vertically and laterally over short distances. The mechanism of shortening, or crowding, of beds by small folds and minor faults is illustrated in Figure 11. Small disharmonic folds tighten gradually upsection so that strata on the oversteepened flanks of the folds are overturned, but beds in the cores of folds dip steeply or vertically. The faulted strata are superposed by bedding-plane faults so that the hinge is thickened; stratigraphically higher beds are pushed upward and outward toward the syncline. Superposition of faulted strata by bedding-plane faults and consequent thickening of the stratigraphic section are common in folds in the Mecca Hills, especially where siltstone and claystone are intercalated within more competent beds of arkose and conglomeratic arkose.

Painted Canyon fault—The Painted Canyon fault is a major structural discontinuity which separates the platform and central blocks (Figs. 4-6). The fault is at least 20 km long and is defined by a zone of crushed rock and fault gouge from a few centimeters to several meters wide. The crush zone is wider in basement rocks (approx. 25 to 40 m) than in the juxtaposed sedimentary rocks (approx. 5 to 10 m). The fault surface is curvilinear, dipping more steeply in canyon bottoms than on adjacent ridges (Fig. 12), showing that it is convex-upward in cross section. Beneath the low-angle segments, footwall strata (platform block) are dragged abruptly to vertical and overturned attitudes (Fig. 13). Locally, strata of the central block are carried short distances northeast over the platform block, either as discrete nappes or as gravity slides, and some of these thrust slices are isolated klippe too small to show on Figure 4.

The central block has been uplifted more than 150 m relative to the platform block as determined from the offset of the basement-sedimentary rock interface in Painted Canyon; the sense and total magnitude of slip could not be determined, however, because of the low angle of intersection made by the fault and the truncated strata, and because marker beds could not be matched confidently across the fault.

The geometry of the Painted Canyon fault and its associated structures is displayed best in the Painted Canyon area (Figs. 4, 5) where the plunge of the structures is steep enough (approx. 25° west-northwest) to permit study of the geometry at several structural levels. Of particular interest is a sequence of strata in the overturned footwall.

FIG. 10—Idealized sketch of mechanism whereby sedimentary cover folds passively over fractured and sheared basement adjacent to fault. For simplicity only one set of possible shear planes is shown. In reality, many sets pervade basement so that basement-sedimentary rock interface is smooth, rather than stepped as shown here. Dashed rectangle indicates approximate part of sketch which is documented by field exposures adjacent to Painted Canyon fault.

FIG. 11—Folding and faulting in core of overturned part of south limb of Mecca anticline, approximately 0.5 km northwest of Painted Canyon. Vertical bedding-plane fault truncates and superposes beds in hinge of fold, resulting in thickening of hinge.
syncline which appears to have been buckled between older and younger strata like pages of a flat-lying book between its covers (Fig. 14). The buckled beds are bounded by a triangular arrangement of low-angle detachment faults which have the following geometries (Fig. 15): (a) those which are convex-upward, flatten gradually away from the main fault, and die out in the bedding (fault A, Fig. 15c); (b) those which are concave-upward, steepen gradually with distance from the main fault, and are truncated at higher structural levels by other low-angle faults (fault B, Fig. 15c); and (c) those which are mainly convex-upward and flatten toward the main fault (fault C, Fig. 15a). The opposite end of the fault either flattens asymptotically into a low-angle fault of the first kind and dies out in the bedding as indicated in Figure 15a, or is truncated by a low-angle fault (Fig. 15c).

Each fault, except fault C, carries older rocks upon younger ones, causing thickening of the stratigraphic section beneath the main fault. Faults A, B, and C bound a triangular domain of tight folds whose axes parallel the main fault plane and plunge 25° west-northwest. Field observations of the folds, faults, and unfolded beds show that faults A and C are detachment surfaces along which the folded sequence in the triangular domain separated from overlying and underlying beds; the observations support the interpretation that the overlying beds merely were pushed up by the buckled wedge of folded strata (Fig. 14). The three interpretive cross sections of this structure (Fig. 15) differ from one another only in the way in which the faults are projected above and below the levels of exposure. We favor interpretation B (Fig. 15) in which the Painted Canyon fault is depicted as a high-angle reverse fault rather than a low-angle thrust fault for two reasons: (1) the Painted Canyon fault dips steeply where observed except where it flattens locally upward into thin nappe-like structures; and (2) the linearity of the trace of the Painted Canyon fault throughout the Mecca Hills strongly suggests that the fault dips steeply or vertically, at least within the realm of its intersection with the surface. The evolution of the structure is given in the following and is illustrated in Figure 16. A basic assumption is that the

FIG. 12—View toward west-northwest of Painted Canyon fault, PCF, 0.5 km northwest of Painted Canyon. Fault, which dips 70° southwest in center of picture, flattens abruptly upward to 20° on skyline ridge. Dotted lines indicate bedding in Mecca, pm, and Palm Spring, Pp-m, Formations.
vertical component of oblique slip dominated during development of the structure:
1. The nonconformity and overlying strata (Fig. 16a) were folded into a sigmoidal configuration (Fig. 16b). The strata define an asymmetric anticline in the central block and an overturned asymmetric syncline in the platform block.
2. With continued flexuring, a master fault (the Painted Canyon fault) developed; simultaneously or following even more uplift, a secondary fault split off the master fault and extended into the strata of the overturned syncline (Fig. 16c).
3. As the fold continued to grow and tighten, the wedge of basement in the footwall, together with part of the overlying sequence of vertical and overturned strata, detached on secondary low-angle thrust faults and moved northeastward like a "piston" into the gentle, southwest-dipping limb of the footwall syncline (Fig. 16d).
4. The "piston" shoved relatively northward and head-on into the southwest-dipping beds, causing them to buckle, uplift, and dilate the entire section; higher in the structure, overturned beds from the central block were thrust short distances on fault D (Fig. 15) over the uplifted, flat-lying beds (Fig. 16e).

![FIG. 14—Interpretive model showing buckling of beds within stratified sequence in footwall (Platform) block of Painted Canyon fault.](image)

Intuitively, it seems clear that such a structure must have formed at shallow depths under low overburden pressure so that the strata could be uplifted bodily above the dilated section. This is supported by the youthfulness of the relatively thin sequence of strata on the platform block where the main effect of erosion has been to cut deep canyons rather than to strip off great thicknesses of strata for which there is no evidence of previous existence.

San Andreas-Skeleton Canyon fault zone—A zone of complexly deformed strata lies between Skeleton Canyon and San Andreas faults (Figs. 4, 5). As shown in Figure 6, the central block has been uplifted relative to the basin block along these two prominent faults. The relatively low structural and topographic relief and the lack of distinctive marker beds permit only the following generalizations:
1. The most recently active trace of the San Andreas fault is clearly marked northwest of Painted Canyon by aligned gulches and ridge notches, offset stream courses, crushed rock and phacoid-bearing gouge, nearly vertical shear surfaces with horizontal slickensides, and en-echelon cracks and fault scarps in alluvium. All of these features are complementary and consistent in indicating right-slip displacement, and it was on this trace about 3 km northwest of Painted Canyon where en-echelon cracks and 1.3 cm of right slip on the fault were triggered dynamically by the Borrego Mountain earthquake in 1968 (Allen et al, 1977).
2. Several distinct, low-angle, west-northwest-trending zones of brick-red, phacoid-bearing fault gouge are parallel with low-angle reverse faults along the San Andreas fault. The faults are convex-upward in cross section and steepen with depth into the main trace of the San Andreas fault. They appear to be similar in geometry and origin to the low-angle segments of the Painted Canyon fault described previously. According to Hays (1957), the displacement on the low-angle
faults southeast of Painted Canyon is oblique, and the magnitude of the horizontal component exceeds the vertical component.

3. The footwall strata southwest of the two faults are folded into asymmetric synclines overturned southwestward. Adjacent to steeply dipping parts of the faults, the folds generally are overturned and appressed (Fig. 17). The axes of the folds are nearly horizontal along the Skeleton Canyon fault, but against the San Andreas fault they plunge from horizontal to as steep as 70°. Locally in such steeply plunging folds, thin beds of mudstone and arkose are deformed into tight, disharmonic folds where they are crowded in the cores of the main syncline. Other investigators have cited the steeply plunging folds, which are about 400 m southeast of the mouth of Painted Canyon, as evidence of strike-slip on the San Andreas fault (Hamilton and Meyers, 1966, p. 520).

4. The exposures of Canebrake-Ocotillo conglomerates 1 km northwest and southeast of the mouth of Painted Canyon show lithostratigraphic evidence of having been displaced about 15 km right-laterally from their source since deposition in Quaternary time (Ware, 1958). The basal part of the stratified sequence consists almost entirely of Orocopia Schist clasts; granitic clasts increase in abundance upsection so that, in the stratigraphically highest exposed part of the sequence, the strata are comprised completely of granitic clasts. Pebble imbrications show that the sources of the clasts were northeast, across the San Andreas fault. Ware (1958) pointed out that the only monolithologic source for Orocopia Schist would have been the Orocopia Mountains, the nearest drainage from which is now 15 km southeast. Thus, as the depositional center was transported northwestward away from the Orocopia Mountains by right slip on the San Andreas fault, the strata received decreasing amounts of Orocopia Schist and increasing amounts of granitic detritus from fans shedding from the Little San Bernardino Mountains.

5. The Skeleton Canyon fault closely parallels and may have been related genetically to the San Andreas fault (Figs. 4, 5). It is a nearly vertical fault which flattens locally upward into low-angle thrust segments carrying the arkosic facies of the upper Palm Spring Formation upon the silty facies for distances up to 500 m (Fig. 18). Evidence for significant horizontal displacement was not found, owing largely to the nearly parallel strikes of the fault and the truncated beds.

6. About 1 km northwest of Painted Canyon (Figs. 4, 5) the Skeleton Canyon fault is folded into an anticline which plunges gently southeast. Beneath the thrust, the strata are deformed into three west-northwest-trending asymmetric folds which are overturned southwestward. Not only are they oblique to and truncated by high-angle segments of the fault, but the tops of the anticlines are "decapitated" by low-angle segments of the fault (Fig. 19).

Cross faults—Steeply dipping cross faults, trending from N 70° E to nearly north, cut the sedimentary rocks of the central block southwest.

FIG. 17—View southeast, parallel with Skeleton Canyon fault, of folded upper Palm Spring Formation, silty facies, in footwall of Skeleton Canyon fault, SCF. Geologist stands in core of overturned syncline.
The geometry of the cross faults with respect to the total structure of the central block resembles a similar structural geometry in the Alpine fault zone of New Zealand (Kingma, 1958). There they are considered to be extension faults formed as a result of finite horizontal separation within a strike-slip fault zone, an interpretation which is confirmed in clay-model laboratory studies (Wilcox et al., 1973) in which extension fractures and normal faults develop parallel with the short axis of the strain ellipse, perpendicular to en-echelon folds. Most of the cross faults shown in Figure 4 are not oriented ideally according to the typical wrench-fault geometry, suggesting that they may have been rotated.

**Basin Block**

The structure of the area southwest of the San Andreas fault zone adjacent to the Mecca Hills was determined partly from detailed gravity studies (Biehler, 1964). The data show a steep gravity gradient of 4,000 m or more in the basement but, because of the complete lack of density-depth control in Coachella Valley (Biehler, 1964, p. 78) and the paucity of surface exposures and well data, a more detailed interpretation of the structure of this domain is not warranted here.

**DISCUSSION AND INTERPRETATIONS**

This study of structural geometries in the Mecca Hills documents three principal observations: (1) a narrow zone of crustal shortening (central block), coinciding with the basin margin, is separated from adjacent, relatively undeformed areas by major strike-slip faults which dip steeply toward the shortened zone, which are convex-upward in cross section, and which have lesser components of reverse-slip; (2) the major strike-slip faults have low-angle thrust segments which extend outward short distances from the shortened

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**FIG. 18**—Oblique aerial view toward northwest of Skeleton Canyon fault, SCF, southwest of Painted Canyon. Low-angle segment of fault carries upper Palm Spring arkosic facies, Ppus, upon overturned syncline in silty facies, Ppus.

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**FIG. 19**—Field sketch of folded arkosic facies of upper Palm Spring Formation thrust over strongly folded silty facies by folded trace of Skeleton Canyon fault. Shaded beds are sandstone. East wall of canyon 1 km northwest of Painted Canyon.
The low-angle segments of the San Andreas, Skeleton Canyon, and Painted Canyon faults are similar to structures which are common along many major wrench faults elsewhere, especially where the faults delimit the base of a steep mountain front. That these low-angle faults steepen abruptly with depth has been documented for other wrench faults having a component of dip slip, such as the Alpine fault in New Zealand (Wellman, 1955), and in California on the San Jacinto fault (Sharp, 1967) and along part of the San Gabriel Mountain front (Whitcomb et al., 1973). Wellman (1955) considered that the surficial thrusting results from downslope creep under gravity, but Allen (1965, p. 84) suggested:

zone; and (3) the basement behaved in a nonrigid, cataclastic manner in the shortened zone. The deformation of the overlying sedimentary rocks was largely a passive consequence of basement-level deformation at shallow depths under low overburden pressure.

**Convex-Upward Faults**

The faults bounding the central block, where observed, steepen with depth and dip consistently toward one another and toward the axis of the central block. This relation is illustrated in Figures 6 and 20a. In both of these illustrations it is assumed that the faults are nearly vertical at depth. As shown in Figure 20b, two-dimensional palinspastic restoration by “unrolling” the folds and restoring the strata back to their probable preforming, prefaulting configurations is geometrically impossible if only dip slip is assumed, if the basement is rigid, and if the sedimentary rocks are not capable of tectonic thickening and thinning. In other words, if the folded strata and the underlying “keystone” of basement are restored to the assumed predeformation positions between the bounding faults, and if the sense of displacement on the faults is purely dip slip and nonrotational, then basement must be “created” to satisfy areal considerations of the restoration. But if oblique slip is invoked, together with nonrigid cataclastic flow of the basement, then the problem is three dimensional, and complex structural reconstructions are possible.

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**FIG. 20**—Schematic illustration showing apparent geometric impossibility of two-dimensional palinspastic restoration of Mecca anticline. a. Idealized present-day cross section. b. Restoration of strata to preforming configuration and resultant space problem at basement level. Area of shaded parts are equal in both diagrams.

**FIG. 21**—Conceptual model of transpression basement deformation. See text for explanation.
Hills, and the Durmid area are evidences of crustal shortening concentrated within a remarkably narrow zone which, from geologic and geophysical data, appears to be less than 3 km wide.

Nonrigid Basement

The limited exposures of basement rocks in the central block are more highly fractured and sheared than their counterparts exposed in the platform block. Moreover, the basement-sedimentary rock contact is not a plane of detachment, even where the sedimentary rocks are folded. These relations are interpreted above as evidence that the basement and overlying sedimentary rocks behaved mechanically as a unit, and that the basement deformed by cataclastic flow by piecemeal slip on the pervasive shear fractures.

We maintain that these observations and interpretations support extrapolation of the deformation mechanism to at least those parts of the central block which are overlain by folded sedimentary rocks. Thus, we postulate that the basement beneath much of the central block has been so pervasively fractured and sheared during a prolonged period of movement in the San Andreas fault zone during Cenozoic time (Crowell, 1962, 1975) that it is no longer mechanically rigid, but as the exposures show in Painted Canyon, it has flowed cataclastically on a large scale in response to regional transpression. By this hypothesis, folding, uplift, and local outward-directed thrusting of the sedimentary succession are consequences of transpressive distortion and resultant uplift of wedges of basement. The mechanism of basement deformation is illustrated in Figure 21. A narrow volume of nonrigid material is constrained between two rigid blocks (Fig. 21A); if the blocks merely were displaced laterally by strike slip (Fig. 21B) the material would deform by simple shear; in transpression (Fig. 21C), however, the material would be sheared and compressed between the two laterally and convergently slipping blocks, so that it would be uplifted out of the shear zone.

A summary diagram of the observations and interpretations of this study (Fig. 22) resembles that of Lowell (1972, Fig. 9) and shows, in a conceptual way, the tectonic relations of the various geometric elements observed in the field and in clay-model laboratory studies of wrench faulting in which transpression is the dominant mechanism of strain.

CONCLUSIONS

Field observations in the Mecca Hills support clay-model laboratory studies in showing clearly
that finite zones of oblique, inward-directed crustal shortening form along wrench faults which, themselves, are driven by deep crustal decoupling in transform margin setting. En-echelon folds and high-angle reverse faults are typical in those parts of the wrench fault zone which are dominated by a transpressive mode of deformation at shallow crustal levels, and they are produced and controlled by cataclastic flow of the underlying crystalline basement. Although the overall resultant geometry of the various folds and faults conforms closely to theoretical and laboratory models, the folds and faults combine locally to form discontinuous complex structures which form small but favorable structural traps for hydrocarbons.

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