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ORIGIN OF LATE CENOZOIC BASINS IN SOUTHERN CALIFORNIA[1]

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ABSTRACT

Several sedimentary basins in southern California, within and south of the Transverse Ranges, display a history suggestive of a pull-apart or a tipped-wedge origin. Beginning in the Miocene, these basins apparently originated along the soft and splintered margins of the Pacific and Americas plates. Basin walls were formed by both transform faults and by crustal stretching and dip-slip faulting. Basin floors developed on stretched and attenuated marginal rocks, and some floors grew as a complex of volcanic rocks and sediments. As basins enlarged, high-standing blocks are pictured as stretching and separating laterally from terranes that were originally adjacent. Older rocks exposed around basin margins therefore cannot always be extrapolated to depth beneath the basins.

Support for such speculative models comes from accumulating understanding of the modern Salton trough. This narrow graben is now being pulled apart obliquely, with faults of the San Andreas system serving as transforms. With widening, the walls sag and stretch, and margins are inundated by sedimentation that goes on hand in hand with deformation and with volcanism within the basin. The Los Angeles basin apparently started to form as an irregular pull-apart hole in the early midMiocene, and basin-floor volcanism accompanied subsequent voluminous sedimentation. Great thicknesses of Miocene beds and volcanic rocks in the western Santa Monica Mountains probably constitute the displaced northern part of the Los Angeles basin, and were laid down adjacent to high ground from which sediments and large detachment slabs were carried into the growing depression. Basins and intervening banks and ridges in the California Borderland may have originated in a broad right-slip regime where strike-slip faults converge and diverge in plan view to slice the terrane into wedge-shaped segments. Displacement along converging and diverging strike-slip faults bounding such wedges results in shortening and elevation, or in stretching and subsidence, respectively.

INTRODUCTION

As knowledge of the geologic history of late Cenozoic sedimentary basins in southern California has accumulated during the past half century, several genetic models have been proposed to explain their origin. At first the great thicknesses of sediments found in deep basins were credited to vertical tectonics only, in which subcrustal processes brought about subsidence of basins concomitantly with the elevation of adjacent highlands. Erosional debris from the highlands was pictured as washing across the basin margins and directly into the contiguous basins. Only slowly did the concept gather acceptance that major strike slip was significant, and was superimposed upon this pattern of vertical tectonics. For example, Eaton (1926) and Ferguson and Willis (1924) noted that strike slip was primarily responsible for the folds along the Newport-Inglewood zone in the Los Angeles basin, and Vickery (1925) interpreted the pattern of faults and folds east of the San Francisco Bay area in terms of strike slip. In the early fifties, rock sequences offset by many tens of kilometers on the San Andreas fault were recognized by Hill and Dibblee (1953), and strike slip of conglomerates from their source areas was shown to be about 30 kilometers on the San Gabriel fault by Crowell (1952). During the two decades since then many workers have demonstrated great strike-slip components on several California faults, including those associated with major basins. As the data have come in, however, it has grown increasingly clear that other faults have essentially no component of strike slip, and that vertical tectonic movements involving steep flexures at basin margins, normal-slip faults, thrust-slip faults and detachment faults are also common. The record shows as well that deformation has been nearly continuous in southern California as a whole since early in the mid-Tertiary, and that this deformation has not always followed the same pattern.

California at present is being deformed as part of a broad transform zone, the sliced and segmented boundary between the Pacific plate and the Americas plate (Atwater, 1970). The origin of several modern basins, such as those within the Salton Trough and the Gulf of California, is related to their position at or near this plate boundary. Similar origins can be recognized for some more ancient basins. The in-

[1] Studies of the tectonics of southern California have recently been supported by the University of California, Santa Barbara, and the U.S. National Science Foundation, Grant GA 30901. I am also grateful to many students and colleagues for numerous discussions and comments and especially to Arne Junger for suggesting a diagram similar to that of Figure 9.

terpretation of the ocean-floor record including magnetic anomalies west of California reveals a history of major plate interaction across the region back into pre-Tertiary times, but detailed explanations of this interaction before mid-Tertiary are still inconclusive. According to Atwater (1970, fig. 17), this interaction since the mid-Tertiary has included long episodes of strike slip, and right slip has predominated in the vicinity of southern California for about 25 million years. The Americas plate has moved about 1500 km relative to the Pacific plate during this interval.

Only about 300 km of post-Oligocene right slip on the San Andreas fault is now recognized in southern California, however, leaving a difference of 1200 km or so in order to match interpretations of the land record with those from magnetic anomalies on the sea floor. This difference can most easily be accounted for by considering that other faults on land, such as those in the Great Basin and splays of the San Andreas in southern California and the adjacent borderland, took up the difference. In particular, a major right-slip fault may have coincided with the western edge of the continent where it joins the deep Pacific floor at the base of the Patton Escarpment (fig. 1). Despite the fact that right slip of the order needed to match the sea-floor interpretation is still not recognized on faults in southern California, in the borderland, or in the Mojave and Colorado Deserts, the idea that these regions are part of a broad transform zone attracts investigation. In this paper we will therefore accept as a premise the concept that southern California and its borderland have been very mobile laterally during the late Cenozoic as part of a broad and complicated transform zone, but without committing ourselves to the magnitude of total right slip across the soft and broad boundary between plates. We will search for models of basin origin and consider ways to recognize or test them.

BASIN GEOMETRY IN A TRANSFORM REGIME

Several types of basins can be envisaged theoretically along a transform boundary between major tectonic plates, and especially if the boundary is a complex zone of branching faults. Some terranes may be uplifted to make source areas, and others depressed to form basins (Crowell, 1974). If the strike-slip zone is distant from land and cuts the ocean floor only, high-standing blocks along the oceanic transform may not rise into the zone of erosion, so that the associated depressions receive little sediment from them. Near continents, however, and especially along continental transforms, large volumes of sediment may be washed directly to nearby basins. Southern California during the late Cenozoic seems to fit the latter circumstances so that the following geometrical discussion starts with the assumption that the transform zone cuts continental crust. Moreover, in using the term 'transform,' emphasis is placed upon the plate-tectonic concept of major crustal plates moving laterally along a strike-slip zone and upon the relation of the strike-slip zone to spreading centers and subduction zones in order to account for lateral displacements of hundreds of kilometers (Wilson, 1965; Vine and Wilson, 1965). In terms of the geometry of rock units, however, such transform faults are major strike-slip fault zones with nearly vertical fault surfaces and long extent. In this sense, they are synonymous with "wrench faults" or "transcurrent faults." In the examples figured below, right slip rather than left slip is illustrated inasmuch as the San Andreas is a right-slip system.

STRIKE SLIP ALONG A STRAIGHT FAULT

If continental terrane with subdued or near-flat topography is cut by a long and vertical strike-slip fault, no differential elevation or subsidence will result from the deformation (fig. 2). The blocks merely slide by each other. With such a simple system there is little likelihood of fault-branching, and fault zones are straight, narrow, and relatively unbraided. Such a situation seems to prevail today along the straight stretch of the San Andreas between the central Temblor Range and the Gabilan Range (fig. 1, TR and GR). This stretch includes Parkfield and the part of the fault zone exhibiting creep and frequent small earthquakes (Brown and others, 1967).

STRIKE SLIP ALONG A FAULT WITH A GENTLE DOUBLE BEND

Displacement of adjacent blocks along a single dominating strike-slip fault with a gentle double curve displays one of two different geometries. On the one hand, the bend may be in the direction to free or release the blocks as they glide by each other, or on the other, to lock or restrain them. With right slip, for example, if the fault trace curves to the right (clockwise) in looking along the fault toward a displaced feature, the bend will be a *releasing double bend*, and if to the left (counter-clockwise), a *restraining double bend* (fig. 3). With left slip, in contrast, a releasing bend curves to the left, and a restraining bend to

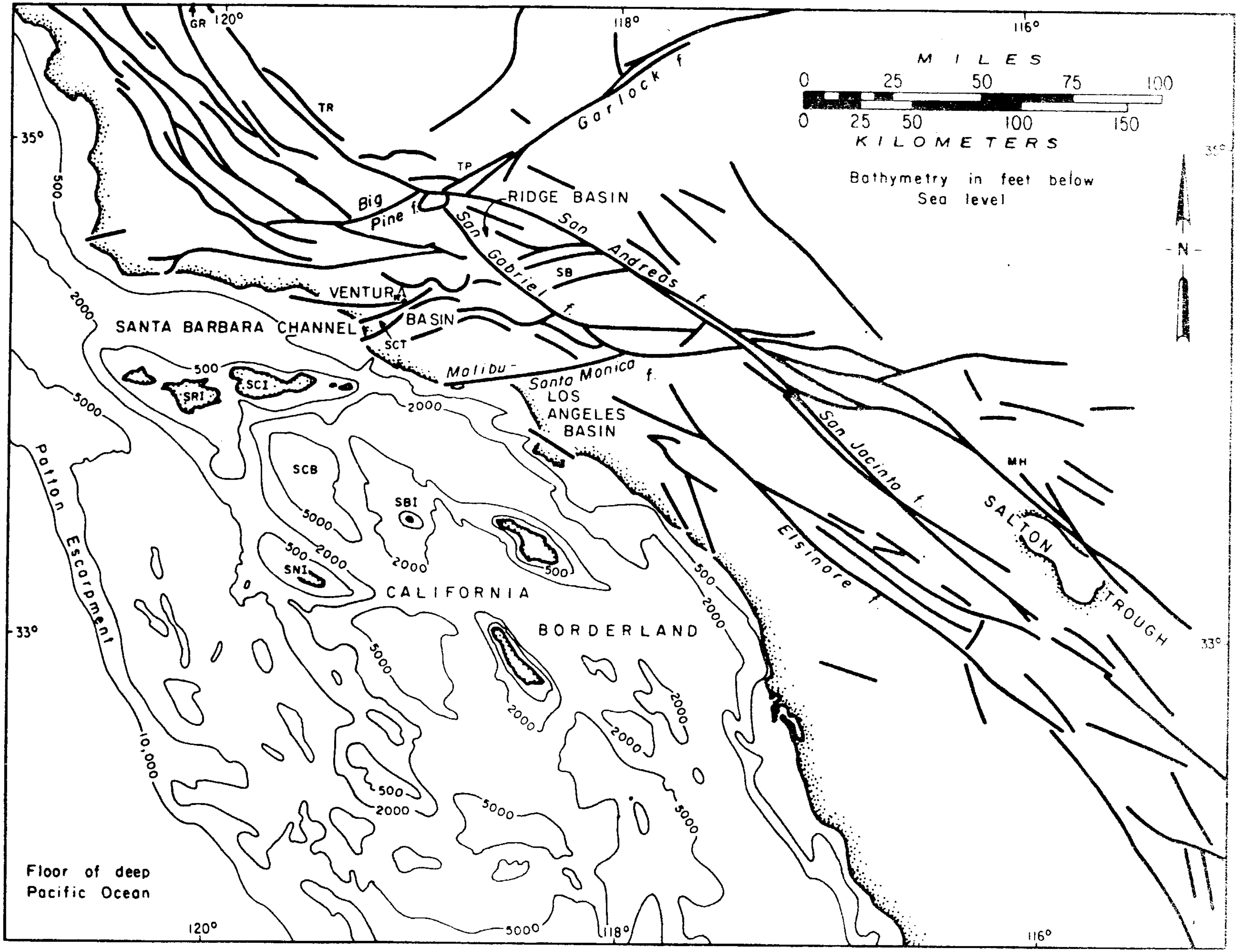

FIG. 1.—Map of southern California and California Borderland showing major onshore faults. Abbreviations: TP, Tejon Pass; SB, Soledad basin; SCT, Santa Clara trough; SRI, Santa Rosa Island; SCI, Santa Cruz Island; SCB, Santa Cruz basin; SBI, Santa Barbara Island; SNI, San Nicolas Island; GR, Gabilan Range; TR, Temblor Range; MH, Mecca Hills.

the right [Note mnemonically that if the two words are the same, a releasing bend results; if different, a restraining bend]. In this discussion the strike-slip fault is visualized as long and extensive, and the bends are relatively local departures in trend. If so, the bends are double in that one curvature takes the fault away from the regional trend and another brings it back into alignment. The direction of shift or strike slip of one block with respect to the other is defined by the strike of the fault on an extensive regional basis. If the fault is considered as a transform fault, this is the direction of relative motion between the major lithospheric plates.

If we consider the blocks as less rigid; that is, as relatively soft and deformable, movement along a fault with a double bend will cause shortening or crowding of the crustal rocks within concavities, and stretching at convexities (fig. 4), in the edges of adjacent blocks. Inasmuch as the crowding and stretching is relieved most easily at the terrane surface, shortening results in elevation of the ground surface, and stretching in subsidence. The maximum effect of these processes occurs near the strike-slip fault and at the point of maximum curvature. As the displacement continues, the centers of elevation or subsidence may move through time. Or on the other hand, one block can remain fixed in shape so that the same terrane continues to be elevated or depressed for long periods as the other block slides by and bends around it. The possibilities range through a continuum from one block remaining fixed in shape as the other participates in all of the bending, to both sharing equally in the bending. And on a single fault this style may change through time.

Ridge Basin, sited adjacent to the Pliocene major strand of the San Andreas fault in the central Transverse Ranges, apparently formed in such a setting (Crowell, 1954; 1962; in press). About 12,000 m (40,000 ft) of both

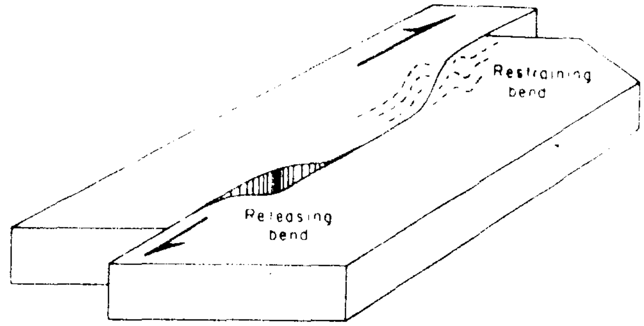

FIG. 3.—Right slip on fault with marked double bends results in pull-aparts at releasing bends and deformation and uplift at restraining bends.

marine and nonmarine sediments accumulated within a narrow basin at the stretched and depressed margin of the Americas Plate as it moved alongside a restricted source area (fig. 4). The lateral movement of the depositional site allowed the accumulation of the vast stratigraphic thickness of sediments by a gradual northwestward overlapping of older strata by younger, but without breaks or unconformities along the axis of the trough as the depocenter migrated. Older strata were carried away laterally as younger ones were deposited opposite the restricted source area. In this case, the uplifted source remained fixed in shape.

STRIKE SLIP ALONG A FAULT WITH A SHARP BEND

A long and straight strike-slip fault with a sharp double bend that sidesteps the fault trend for a relatively short distance can exhibit again two basically different situations. A sharp restraining double bend results in overlap and elevation at the bends (fig. 5), and a releasing double bend results in a pull-apart and subsidence (fig. 6). At restraining bends, geologic structures display oblique shortening, and at releasing bends, stretching or extension.

Restraining double bends bring about overlap

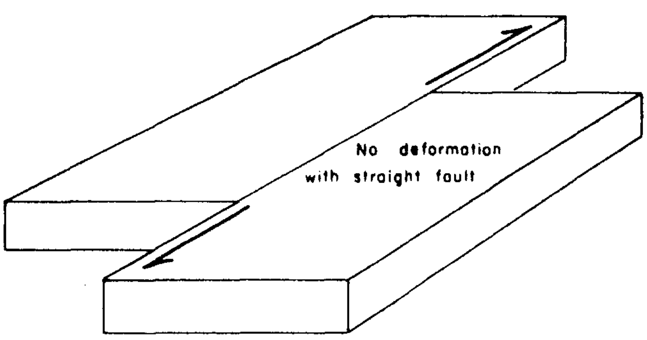

FIG. 2.—Strike slip on straight fault results in no deformation of crustal blocks.

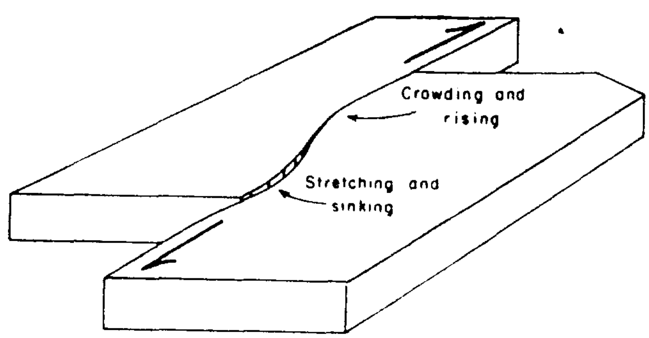

FIG. 4.—Right slip on gently curved fault results in crowding and uplift within convexities of deformable lithospheric plates and stretching and sagging within concavities.

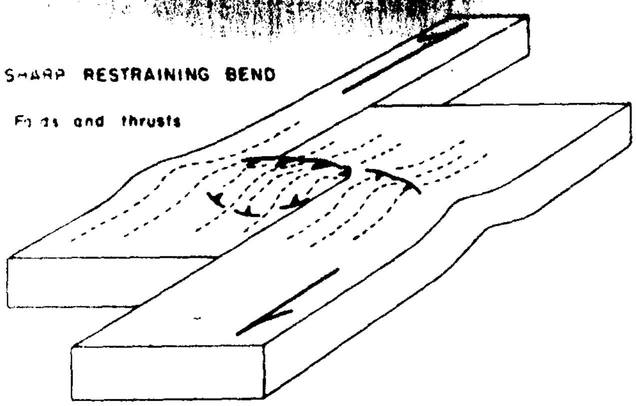

FIG. 5.—Severe deformation at sharp restraining bend results in folds and thrust faults.

of one block over the other, so that, under gravity, the edge of one block is depressed to form a shallow site for sedimentation adjacent to an elevated source area (Crowell, 1974, fig. 6). An example may be the depositional site of the wedge of continental sediments now accumulating on the San Bernardino Plain southwest and adjacent to the San Andreas, which at this place marks the boundary of the San Bernardino Mountains.

In contrast, releasing double bends form deep and narrow sedimentary basins at the pull-apart. These range in scale from small sag ponds within a restricted strike-slip zone floored by local country rock to true rhomobchasms (Carey, 1958), such as those in the Gulf of California, floored by new lava above a spreading center or diapiric volcanic complex. Large and complex pull-aparts are treated more fully below.

BRANCHING AND BRAIDED STRIKE-SLIP ZONES

Strike-slip systems, such as those in California, consists of long and straight master faults with lesser branching faults or splays leading off from them. In addition, many of the major faults within the system are fault zones several kilometers wide containing fault slices and folds (Saul, 1967). Major splays lead away from places where there is a slight change in strike of the master fault. In fact, where the Sunol-Calaveras system extends northward and away from the San Andreas near Hollister, the San Andreas northwest of the juncture is not now as active seismically and a crustal wedge may be forming (Burford and Savage, 1972). The inference is that the local northwestern part of the San Andreas is in the process of being supplanted as the major transform break by the Sunol-Calaveras in response to adjustments between the Pacific and Americas plates.

The splay may either continue on the new trend, or rejoin the original master fault to make a wedge or slice (fig. 7). Wedges range in size up to more than a hundred kilometers in length, such as the one between the San Gabriel and San Andreas faults within the Transverse Ranges. If huge wedges of this type are tipped longitudinally as displacement on the transform system continues, one end may subside to form a depositional site, and the other may elevate to provide a source area. Some further generalizations concerning broad zones of slices and wedges are discussed below.

Braided fault zones consisting of anastomosing faults and obliquely trending folds, such as the Sunol-Calaveras fault zone (Saul, 1967), may display local complexities that have only obscure kinematic relations to strike-slip origin. Individual faults exhibit dip slip and dip separations. Some originated as wedges within the zone were squeezed upward and others, during sagging of wedges downward. Clay-model experiments, such as those illustrated by Wilcox and others (1973), show these complicated patterns very well. Rocks on a regional scale

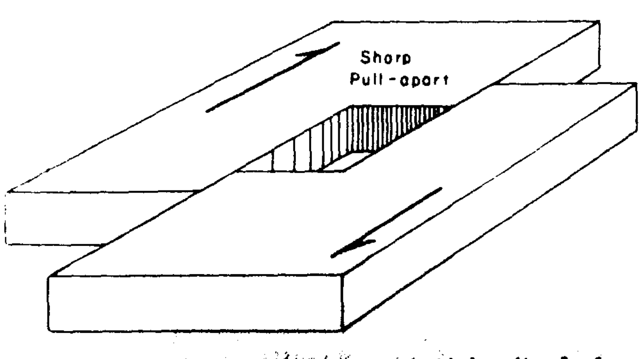

FIG. 6.—A sharp pull-apart on a right-slip fault.

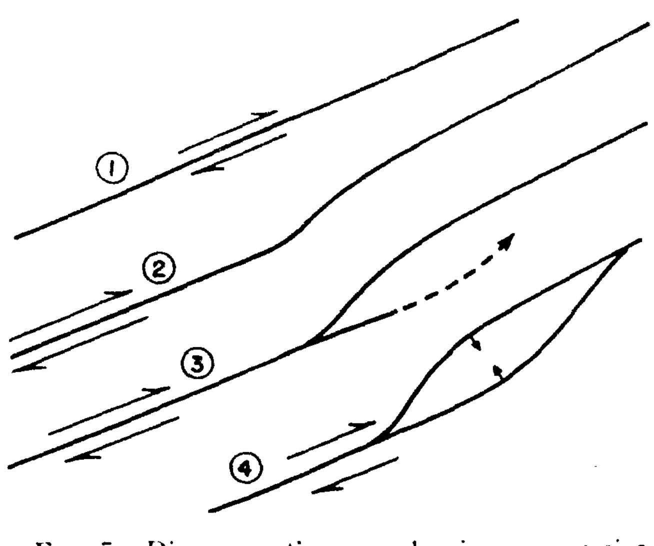

FIG. 7.—Diagrammatic map showing progressive development of fault splays and wedges on a right-slip fault. Straight fault (1) gradually develops a bend through time (2 and 3) and eventually forms a fault wedge (4).

are also weak, similar to clay, so that when a crustal block is pressed upward beside a nearly vertical fault, the hanging well sags outward and downward; the field geologist will correctly map it as a thrust fault. Such an origin for local complexities has been described, especially in New Zealand where horsts and grabens are associated with strike-slip zones (Kingma 1958; Lensen, 1958). Similar braided zones are recognizable in Maritime Canada (Belt, 1968), northwestern Scotland (Kennedy, 1946; Dearnley, 1962), along the Dead Sea fault zone of the Levant (Quennell, 1958; Freund, 1965), and along the north coast of South America in Colombia, Venezuela, and Trinidad (Malfait and Dinkelman, 1972; Wilcox and others, 1973; Crowell, 1974).

PULL-APART BASINS

At the present time the Gulf of California and Salton Trough are widening and lengthening as continental terrane to the west moves obliquely away from the mainland part of North America (Wegener, 1924; Carey, 1958, Fig. 42; Hamilton, 1961). This process is envisaged as the result of sea-floor spreading along the segmented and offset parts of the East Pacific Rise as it enters the Gulf of California at its southern end (Larson and others, 1968; Moore and Buffington, 1968; Larson, 1972; Larson and others, 1972). Geologic studies and geophysical surveys at the head of the Gulf and within the Salton Trough suggest that the Salton Trough lies above a series of spreading centers or diapiric masses with volcanic rocks at depth, and continental rocks, if any, are attenuated and fragmented near the center of the structure (Elders and others, 1972; Sumner, 1972; Henyey and Bischoff, 1973; Karig and Jensky, 1973). It is therefore probably a true rhombochasm, or chain of them, that has opened while abundant sediment has flooded into the widening hole (Crowell, 1974). Details of the structure along the northeastern border of the Salton Trough, for example, fit reasonably well the idea that they are the consequence of right slip at a steep basin margin with high-standing continental rocks on the northeast and deep quasi-oceanic crust on the southwest. In the Mecca Hills (fig. 1, MH) the deformed sedimentary section of Neogene age thickens rapidly toward the trough and the San Andreas zone there consists of braided faults of several ages, with complex folds and thrusts arranged between them (Dibblee, 1954; Hays, 1957; Crowell, 1962).

According to a pull-apart model, prisms of the oldest sediments lying upon the original basin floor should occur around the margins

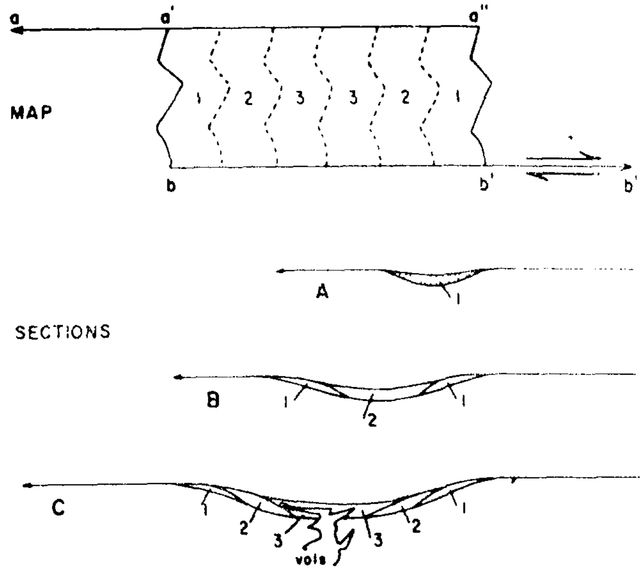

FIG. 8.—Sketch map and sections of pull-apart basin; see text for discussion.

only, but drilling and geophysical studies are not yet complete enough for confirmation. In the paragraphs below I will consider first some simple theoretical models and then geological processes and circumstances that complicate and modify them. The latter include especially the relative rates of sedimentation in comparison with rates of subsidence and deformation, changes in orientations and rates of deformation through time, and the strength or weakness of the crust and the magnitudes and arrangements of heterogeneities within it.

The simplest pull-apart model consists of side-stepped parallel transforms (a-a′-a″ and b-b′-b″ in fig. 8) sited above a volcanic center. The transform margins (a-a″ and b-b″) of the basin appear straight and parallel in map view, but the pull-apart margins (a′-b and a″-b′) can have any shape and are here drawn crookedly to emphasize their critical geometric distinction from the transforms. When the pull-apart is born, a′-b and a″-b′ fit together, but as the hole opens, the pull-apart walls sag independently. The walls extend and stretch, so that in time their structures may be very different and fail to match, although details in preexisting rocks will still correlate. The walls along the transform margins of the pull-apart tend to sag also but continued strike-slip on them slices off segments out of line, and a complex braided zone results.

The first sediments laid down within the growing basin occupy a position as in figure 8, stage A, and the later layers are shown in stages B and C. As the hole widens, the margins are first stretched but in time lava comes up from below (stage C) so that down-dip near the center of the basin lavas and shallow intrusions

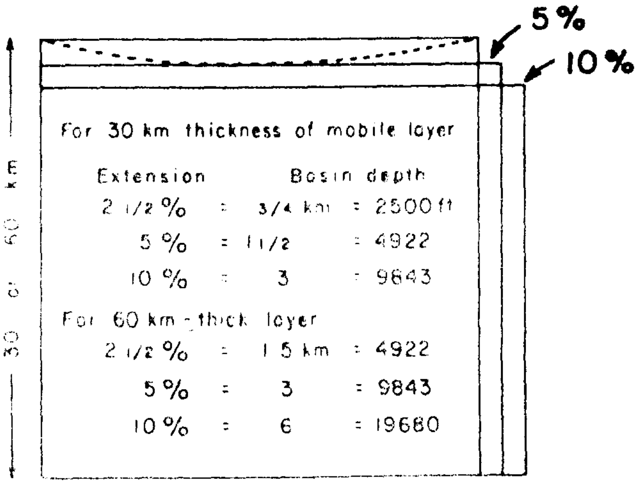

FIG. 9.—Diagram showing crustal cross section, 30 or 60 km thick, with 5 or 10% extension; see text for discussion.

may document extension. The emplacement of such lavas over active spreading centers or over diapirs from the mantle is suggested by gravity and heat-flow data and by the location of geothermal areas and young volcanics in the Salton Trough (Elders and others, 1972). It is also suggested by the distribution of volcanic rocks within the deeper and older parts of the Los Angeles basin, now displaced laterally, uplifted and eroded to view in the western Santa Monica Mountains.

Inasmuch as the crust is weak and easily folded, faulted, stretched, and compressed on a regional scale, some basins probably form in a broad transform system without volcanic flows and intrusions at depth. Most of the basins in the southern California region, including the Gulf of California and the continental borderland, range between 50 and 100 km in a northwest-southeast dimension. Inferences from the depths of earthquake foci along the San Andreas system (Eaton, 1967) and from plate-tectonic models (e.g., Isacks and others, 1968) suggest that although creep takes place below a depth of about 20 km, there is a near-uncoupling of the crust from the upper mantle at or within the low-velocity zone. Under stable cratonic crusts, the thickness of the lithosphere or depth to this zone of uncoupling is of the order of 110 km, under the central Great Basin about 20 km, and in the oceans away from ridges about 75 km (Walcott, 1970).

It may be of interest to estimate the amount of crustal extension needed to form a basin such as those in the California Borderland. For a rough and oversimplified two-dimensional model, if we assume that the lithosphere in southern California has a minimum thickness of 30 km beneath fragmented sialic crustal blocks and a maximum thickness of 60 km and that the average basin has an average depth across the block of 3 km and a northwest-southeast dimension of 60 km, then the extension needed to form the basin is 5 percent for the 60 km lithospheric thickness and 10 percent for the 30 km thickness (fig. 9).

Unfortunately, as yet we have no clear picture whether stretching or "necking down" of the lithosphere as much as 5 or 10 percent is reasonable. We can conclude, however, that stretching of crustal blocks of a few percent may begin the pull-apart process and start the formation of the basin before rupture of the basin floor and the entry of volcanics from below. In fact, in a broad weak transform zone, such as may prevail across the full width of southern California and its borderland, the volcanics may arise irregularly and diapirically into the growing gap after the breaking point is reached. At the same time the basin is being filled from the top by sedimentation.

In figure 8, the sidestepped transforms are shown as ending at a″ and b, but as the hole enlarges, complications at these corners are to be expected, such as continued minor growth along extensions of the transforms. Moreover, the angle between the transform direction and the pull-apart scarps (a′-b and a″-b′) might be very much less than shown in figure 8 so that in the field it would be difficult to locate the basin corners precisely. As the basin deepens, the pull-apart margins may stretch and subside through time, so that successively younger stratigraphic units lap farther and farther basinward leaving behind a record of minor unconformities. If the center of the basin has stretched to the point of rupture, and then has been intruded by volcanics to make a new floor, strata deposited earlier within the basin may be confined to the attenuated margins only and a deep well drilled in the basin center would not penetrate them. Instead, it would pass through younger sediments and into lava flows and associated volcaniclastic rocks. Below these it would drill through fragments only of the earlier basin fillings, and of the basin floor, and finally into diapiric masses of hypabyssal volcanics and volcanic feeder complexes. Such a model at depth suggests that it is unwise to extrapolate strata at the pull-apart margins very far down dip into some basins. The floors of true rhombochasms, for example, consist of new volcanic rocks, and lack the older rocks exposed around their margins, except perhaps as isolated blocks or "floaters." A summary sketch map is shown in figure 10, on which are portrayed possible features associated with pull-apart basins, but no single basin would be expected to possess them all.

FAULT-WEDGE BASINS

In regions such as southern California, and especially within its borderland, rhomboid and lens-shaped basins are associated with similarly shaped high-standing banks and ridges. Such a fragmented portion of the continental plate can be visualized theoretically as forming within a strike-slip regime if the major strike-slip faults converge and diverge in map view. For example, in a right-slip system where two major right-slip faults converge, assuming concurrent or intermittently alternating movement on each, the wedge between the faults will be compressed and elevated where the faults diverge, the block is extended and terrane subsides (fig. 11). Many faults in a broad and anastomosing system probably do not all move at the same time; those that predominate become straighter and longer, whereas some early faults are bent and rotated out of an orientation conducive to easy slip.

Ideas developed by Lensen (1958) to explain horsts and grabens and changing fault dips along strike-slip fault zones in New Zealand can be modified to apply to broad transform

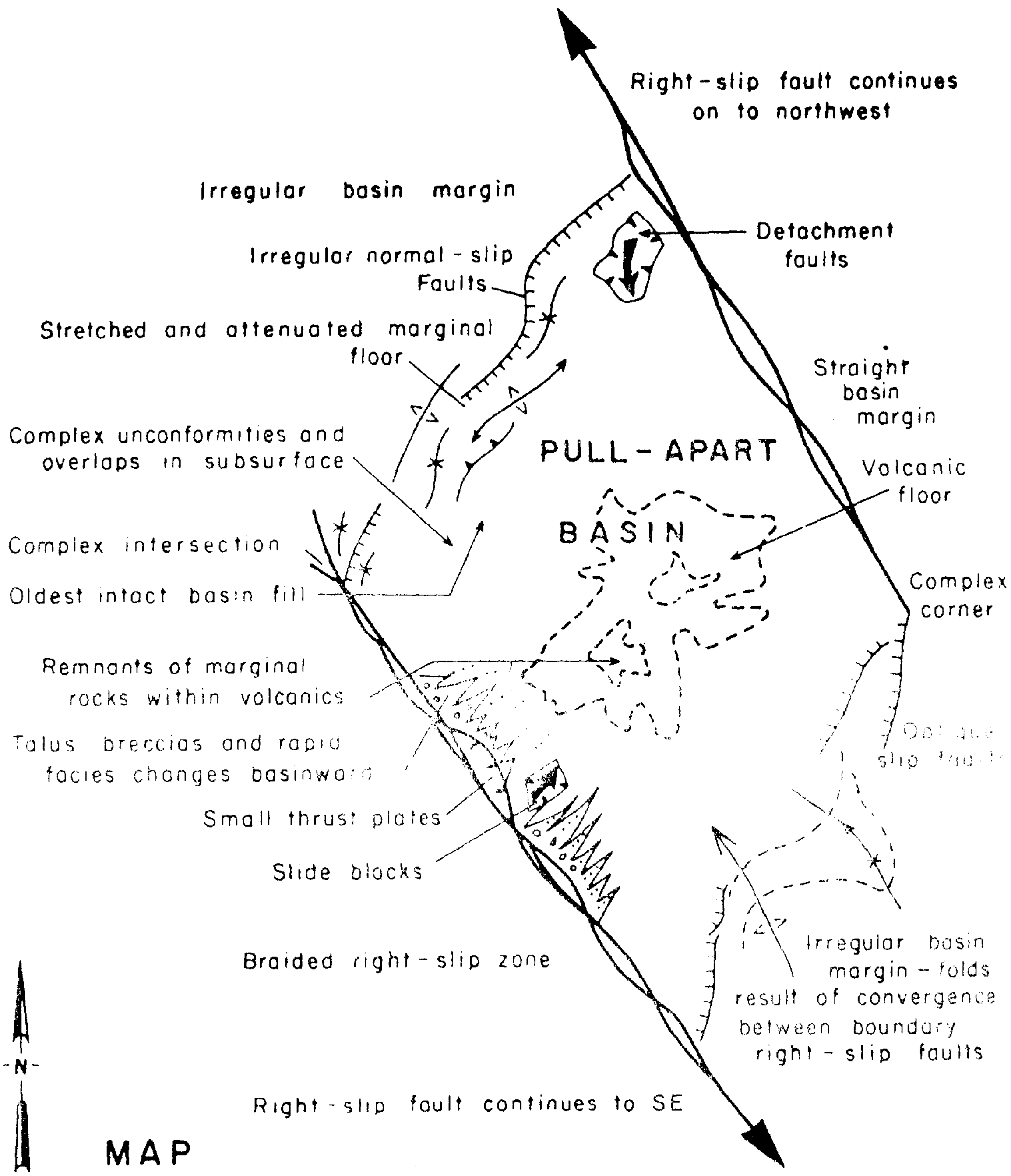

FIG. 10.—Sketch map of idealized pull-apart basin; see text for discussion.

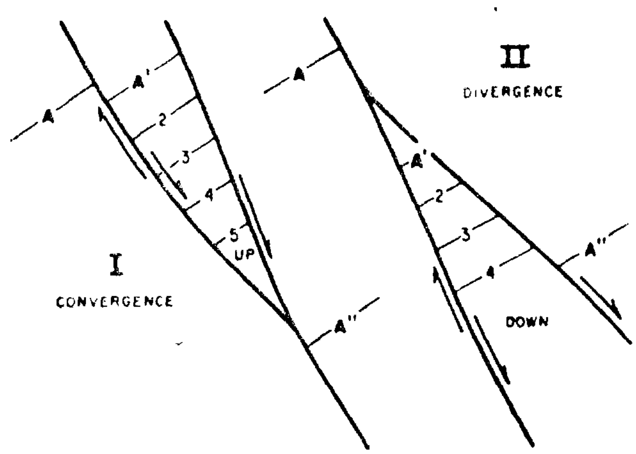

FIG. 11.—Sketch maps showing uplift of tip of fault wedge with convergence of right-slip faults, and subsidence of tip with divergence; see text for discussion.

borders in plate tectonics. If Lensen's concept of the principal horizontal stress is replaced by the concept of the direction of relative motion between two major plates, many of his geometric relations apply. The plate-motion direction will lie at 45° to this direction of principal horizontal stress. Ideally, in plate-tectonic theory, rigid plates glide by each other along a straght transform and the relative motion between the two plates is purely horizontal on a single vertical fault surface. At the present time this direction of relative motion is determined by measurements of the first motions of earthquakes, and by noting the orientation of the long and straight and predominating strike-slip faults that are clearly active.

In a boundary region of weak plate edges between rigid plates, however, braided zones apparently develop. In these systems some faults lie parallel to the direction of relative plate movement whereas others lie at an angle, usually a small angle. In general, those parallel to the plate-movement direction predominate and grow longer; those at an angle may rotate even farther out of alignment. The long predominating faults develop nearly vertical dips; those rotated out of alignment develop dips that depart considerably from the vertical. Strike-slip faults curving or bending away from the plate-movement direction gradually change from pure strike slip upon a vertical fault surface to those with first gentle oblique slip and then steep oblique slip as the fault strike bends more and more. If the curvature carries the fault into a region of extension, the fault becomes a normal oblique-slip fault; if into a region of compression, a reverse oblique-slip fault.

Such geometric relations are especially easy to envisage along braided zones of single major strike-slip faults where all slices occur in surficial rocks. Along such master faults, the faults bounding the slices converge at depth to rejoin the strike of the through-going fault. In regions such as the California Borderland, however, the major faults do not meet at depth, but presumably end in the lower crust in approaching the low-velocity zone. Such a system, including pull-apart basins, highs owing to convergence, and lows owing to divergence between major right-slip faults, is shown in figure 12.

SOUTHERN CALIFORNIA BASINS

Salton Trough, an example of a pull-apart basin, and Ridge Basin, an example of a basin formed by the saggng of weak crust as plates move around a double bend, have been mentioned briefly above. It remains to comment concerning the applicability of models described above to other basins in southern California but some complicating factors need emphasis first. To begin with, the tectonic style across southern California has changed from place to place during the last 25 my so that older basins originated under different tectonic schemes from modern ones. Salton Trough, for example, originated during the past 4 to 6 my and all deformation of Pliocene and Quaternary age can probably be related somehow to this opening. The San Andreas fault in the Salton region, however, is older than this event and was associated with an earlier elongate basin or proto-Gulf (Crowell, 1971; Karig and Jensky, 1973).

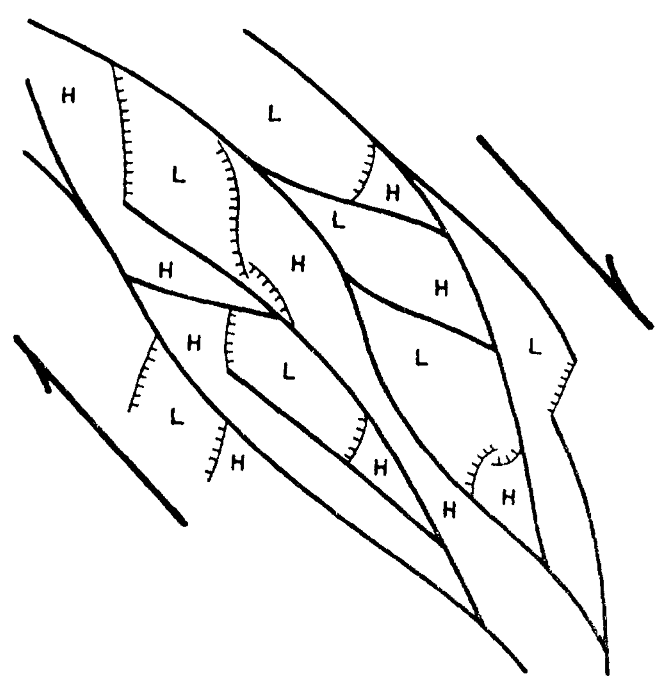

FIG. 12.—Sketch map of region in a transform regime, showing pull-apart basins and tipped fault wedges where right-slip faults converge or diverge; see text for discussion.

During the Quaternary the Transverse Ranges were deformed and uplifted as shown by the age of recent movements on dip-slip faults bounding the range and the age of folding (Crowell, 1971; Dibblee, 1971; Ehlig, in press). In fact, the San Fernando Earthquake of 1971 demonstrates that this deformation is still in progress (Grantz and others, 1971). Moreover, the major bend in the San Andreas fault near Tejon Pass (fig. 1, TP) and the origin or rejuvenation or reorientation of many structures in the region are perhaps all associated with the relative northwestward movement of the Peninsular Ranges toward the Transverse Ranges that accompanied the opening of the Gulf of California. Earlier events in southern California included major left slip in an east-west direction on the combined Malibu Coastal-Santa Monica fault system and Whittier-Elsinore fault system of as much as 90 km in the latest Miocene or early Pliocene (Yerkes and Campbell, 1971; Campbell and Yerkes, 1971), displacement on faults associated with opening of the Los Angeles basin in the early mid-Miocene, and the formation of steep and narrow grabens in the Soledad basin (fig. 1, SB) in the early Miocene (Jahns and Muehlberger, 1954; Crowell, 1968). Deformation in southern California has therefore been locally severe and intermittently continuous during the late Cenozoic as sedimentation and erosion have gone on concomitantly. Older stratigraphic units and structures have been modified by these processes so that we may not easily identify the original basin geometry. Careful palinspastic work, in which the results of younger deformations are first removed, must precede analysis in detail of basin tectonics in the past. This sound procedure, however, is difficult and imposing, and is well beyond the scope of this brief paper.

THE LOS ANGELES BASIN

One of the regions of southern California that displays this type of complicated history is the Los Angeles basin (fig. 13). It contains over 6750 m (22,000 ft) of Miocene and Pliocene sediments in its deepest part and has yielded nearly 6 billion barrels of petroleum to date (Gardett, 1971, table 1). The basin was completely filled with sediments by some time in the Pleistocene and is now being deformed, especiallly along the Newport-Inglewood trend (Harding, 1973; Yeats, 1973; Hill, 1971). Faulting and folding along this trend fit neatly into the concept of deformation along a system of simple right shear in a thick sedimentary section overlying a major fault at depth (Eaton, 1926; Platt and Stuart, in press). This buried fault, however, was primarily active before deposition of the upper Miocene and Pliocene sediments, although it was probably active and instrumental in demarcating the western margin of the basin in early mid-Miocene times. The San Onofre Breccia, for example, was laid down to the east of a fault scarp along this trend during the early part of the middle Miocene; the debris came from a schist terrane, probably exposed to subaerial erosion (Woodford, 1925; Stuart, 1973), that bordered the basin on the west. During the later Miocene, however, the fault was overlapped and marine beds transgressed southwestward.

The southeastern margin of the Los Angeles basin is formed by deformed Cretaceous and lower Tertiary strata overlying Mesozoic sialic basement. Facies trends, particularly in Paleocene beds, show that the paleocontours extended approximately in a north-south direction, with marine waters deepening westward. Nonmarine beds succeeded these in the Oligocene and early Miocene (Sespe and Vaqueros formations) but with approximately the same depositional trends. Similar stratigraphic successions older than middle Miocene are recognizable in terranes surrounding the Los Angeles basin and were disrupted by tectonic processes involved in the origin of the basin (Yerkes and Campbell, 1971; Campbell and Yerkes, 1971). Marked sedimentation within the deepening Los Angeles basin ensued in the middle Miocene, and was quickly followed by both faulting and volcanism in this southeastern region. In the San Joaquin Hills (fig. 13, SJH), for example, irregular north-trending faults displace middle Miocene strata but in turn are intruded by middle Miocene volcanics (Vedder and others, 1957). In addition, some of these faults are also overlapped by upper Miocene beds (Monterey Formation). The continuity and complexity of faulting and deformation along this flank of the Los Angeles basin is emphasized by the fact that some faults of similar trend are clearly younger and truncate the volcanics and Monterey beds. Volcanic rocks are present nearly everywhere in the central part of the Los Angeles basin (Eaton, 1958; Yerkes & others, 1965, fig. 9), and imply a nearly hydrostatic uprising of lava to a compensating level within the basin. Only locally were volcanic rocks extruded at and beyond the basin margins, as in the Glendora region (Shelton, 1955; fig. 13, GV).

During the middle Miocene the Los Angeles basin extended northward beyond the limits of the present Los Angeles Plain. The western Santa Monica Mountains, for example, contain very thick sequences of flyschlike strata of this age that extend downward into the lower Miocene. The beds were probably deposited in fairly

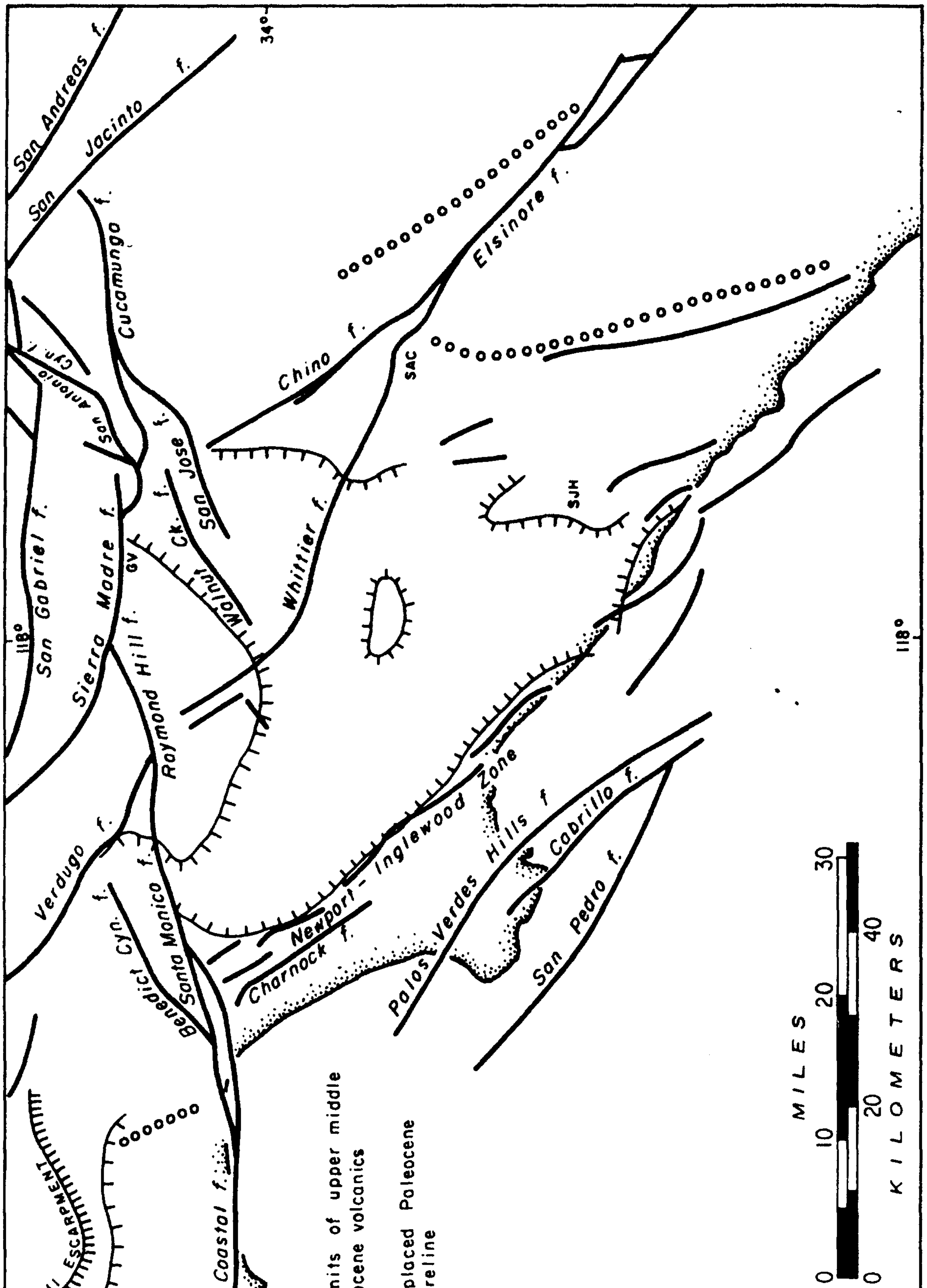

FIG. 13.- Sketch map of the Los Angeles basin region. Abbreviations: GV, Glendora volcanics; SAC, Santa Ana Canyon; SJH, San Joaquin Hills.

deep water with a nearby schist landmass on the southwest (Woodford and Bailey, 1928; Durrell, 1954) and with a coast to the north near the Simi Escarpment (fig. 13). Within this trough the lower and middle Miocene beds reach a total thickness of about 3800 m (12,500 ft) and are intercalated with middle Miocene volcanics aggregateing an aditional 3650 m (12,000 ft) approximately. The middle Miocene section is overlain by about 1400 m (4500 ft) of upper Miocene sandstone and shale. This very thick sequence of clastic sediments, now deformed and uplifted, thins northward very rapidly toward the Simi Escarpment. According to Campbell and others (1966), detachment blocks from the region of this escarpment slid southward into the deep basin during the mid-Miocene. Since these events the whole region has been displaced relatively westward with respect to the main part of the Los Angeles basin by left slip on the Malibu Coastal-Santa Monica fault system (Yerkes and Campbell, 1971; Campbell and Yerkes, 1971). Even more recently, during the Pleistocene, the Santa Monica Mountains were uplifted and deeply eroded. Upper lower and lower middle Miocene sandstone and shale, here considered as laid down in a deep part of the original Los Angeles basin, are now exposed to view along portions of the Malibu Coast. Dike and still complexes with associated flows document extension and perhaps afford an arrested view of the floor of a widening pull-apart basin.

During the Pliocene, the Los Angeles basin deepened but became considerably restricted. Thick sediments accumulated south of the present location of the Santa Monica Mountains and southwest of the Whittier fault zone (fig. 13.) This fault apparently originated near the end of the Miocene because middle Miocene beds are displaced nearly as much as Pliocene (Woodford and others, 1954, p. 75). It apparently formed the northeastern boundary of the Pliocene basin, but may have terminated at the southeast in a "corner" near Santa Ana Canyon (fig. 13, SAC). On the west, Pliocene beds overlapped the Newport-Inglewood fault zone and on the plunging southeastern margin of the basin overlapped as well upon deformed older strata. Subsidence, presumably accompanying extension and stretching and attenuation of crustal rocks, allowed the accumulation of thick sediments in the center of the Los Angeles basin. No volcanics are known to have invaded the basin floor during the Pliocene, either because extension was not sufficient to require it or because a hot spreading center did not then lie beneath it.

By the Pleistocene the Los Angeles basin had filled with sediment and shortly thereafter the beds were deformed, especially along the northeastern margin, demarcated primarily by the Whittier fault zone, and over the buried Newport-Inglewood fault zone (Harding, 1973; Yeats, 1973). The Elsinore fault system originated as a major strike-slip fault late in the Pliocene or in the Pleistocene (Gray, 1961), perhaps associated with the relative northwestward movement of the Peninsular Ranges as the Gulf of California opened. In addition, the San Jacinto fault to the east, with a total right slip of about 24 km (Sharp, 1967), may have resulted from the same movements. The southeastern part of the Elsinore fault, however, apparently has a right slip of only about 5 km, judging from the offset of an ancient cataclastic zone (R. V. Sharp, p. 22, in Lamar, 1972). The Elsinore fault is therefore probably younger than much of the movement on the Whittier fault with which it is now connected, and both faults are younger than the original opening of the Los Angeles basin in the early middle Miocene.

Bouguer gravity anomalies over the Los Angeles basin now show a broad and deep depression corresponding roughly with the thickest section of upper Miocene and Pliocene strata (McCulloh, 1960). The gravity measurements apparently reveal the thick mass of light sediments in the basin and not a high-standing diapir or volcanic complex derived from the upper mantle similar to that inferred to lie beneath the Salton Trough from high values of gravity and other data in that region (Elders and others, 1972, Fig. 3). More complete deep seismic and other geophysical data are needed before we can understand the structure at depth below the Los Angeles region, and before we can reconstruct the deeper structures formed by tectonic events in the late Cenozoic leading up to the present.

The history of the Los Angeles basin as we now understand it includes birth accompanied by rapid deepening during the early middle Miocene followed by thick sedimentation and volcanism, especially in the central part. Detachment faulting took place along the northern margin in the mid-Miocene. Truncation and left displacement of the irregular northern portion of the basin occurred in the late Miocene or after, and were accompanied by death of the Newport-Inglewood zone and nearly simultaneous birth of the Whittier fault zone. Thick sedimentation in the restricted Los Angeles basin followed during the Pliocene. The history ends with Pleistocene filling and northwest-southeast compression manifested by birth of the Elsinore fault and complex right-slip reactivation along the Whittier fault zone. Although it is speculative, perhaps the original basin was born as a pull-apart over a "hot spot"; this may have been associated with the passage of the East Pacific Rise along the coast, or with a local hot "plume."' Later events in the Los Angeles basin, however, are less clearly related to a pull-apart origin.

OTHER BASINS

The California Borderland consists of a series of irregular topographic highs, some surmounted by islands, separated by basins (fig. 1). Those basins near the coast and accessible to debris from rivers in general contain more sediment than those far offshore and relatively isolated from land sources (Emery, 1960, p. 53; Moore, 1969, pl. 14). Extrapolation seaward of the land geology and geologic history into this region suggests a complex history similar to that just reviewed for the Los Angeles basin. Data to document the complicated history are however missing from the published record. In general, the pattern of escarpments, the shapes of banks, and ridges and islands, and the configuration of basins, suggests a pull-apart origin for some of the basins. This pattern is similar to that shown here in figure 12, consisting of diverging strike-slip faults in a broad and soft transform zone. The shape of the Santa Cruz basin (fig. 1, SCB) suggests that it is a pull apart formed when the ridge surmounted by Santa Barbara Island (fig. 1, SBI) was stretched away from the ridge connecting Santa Rosa Island and San Nicolas Island (fig. 1, SRI and SNI). Although other analogies between the style of deformation portrayed on figure 13 and the California Borderland can be recognized, it is not profitable to speculate further here in the absence of specific information. Nonetheless, such a pull-apart origin for some basins, associated with convergence and divergence along major strike-slip faults accompanied by attendant rising and tipping of fault-bounded wedges, should be entertained by geologists and geophysicists investigating the region.

The Ventura basin, and its offshore extension beneath the Santa Barbara Channel (fig. 1), may also have subsided in a regime of stretching. During the Pliocene, for example, the Santa Clara trough (fig. 1, SCT) received more than 4600 m (15,000 ft) of sediments that were then severely compressed in a north-south direction during the Pleistocene (Nagle and Parker, 1971, Fig. 12). In the absence of known Pliocene volcanism at depth, however, there is little reason to suggest that the trough formed as a true sphenochasm or rhombochasm (Carey, 1958).

SUMMARY AND RECOMMENDATIONS

Understanding of the origin of the Salton trough and other basins along the San Andreas transform, now active, leads to the speculation that more ancient basins in southern California may have originated in a similar way. The geologic record is so complicated, however, that in this paper we have focused attention on what we ought to look for in order to find analogies rather than on documentation. In a strike-slip regime, pull-apart basins or rhombochasms will display straight margins where they are parallel to the transform direction, and irregular borders along the pull-apart margins. The transform margins although generally straight will be complicated in detail, and will consist of braided zones, slices, thrust blocks, and detachment faults where high terranes are structurally unsupported against low terranes. Pull-apart margins may display similar features, but even more irregularly. If pull-aparts stretch enough, or are sited above hot spreading centers or diapirs of magma from the upper mantle, volcanic rocks may enter their floors as dikes, sills, irregular bodies, and flows. Under such circumstances the floor of the basin may consist of volcanic rocks and young sediments deposited in the depression, and old or marginal rocks may be absent or present only as isolated blocks or "floaters." Structure and strata exposed around the margins of such pull-aparts cannot be extrapolated to the basin floor with confidence.

A system of anatomosing transforms, converging and diverging in map view, may give rise on a regional scale to wedge-shaped basins separated by uplands. In a soft crust, convergence of faults will result in squeezing of the terrane between the faults and in its deformation and uplift owing to isostatic compensation. Divergence of strike-slip faults will result in stretching and sagging, and the development of down-tipped triangular basins and pull-apart basins. Many of the latter will be rhombic in shape, and some may have floors composed of volcanics intermixed with infilled sediments with few or no remnants of previously existing crustal rocks. Inasmuch as much stretching and sagging and squeezing and uplift goes on hand in hand with sedimentation, complicated unconformities and overlaps are to be expected within the basins, and especially around their margins. Kinematics interpreted from local structures may therefore reveal only remotely their connection to a broad strike-slip regime.

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