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# Late Quaternary Structural Evolution of the Western Margin of the Sierra Cucapa, Northern Baja California

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## ABSTRACT

The western margin of the Sierra Cucapa is defined by the Laguna Salada fault, a complex zone of active oblique-dextral slip faults. The northwestern section of the fault zone consists of a single fault strand which has had an oblique-dextral sense of slip throughout the late Pleistocene and Holocene. The southeastward continuation of this single fault strand has been comparatively inactive during the Holocene. Slip during the late Quaternary has instead been stepped several hundred meters to the southwest onto two distinct oblique-dextral fault strands. The easterly strand extends southeastward and intersects the Cañon Rojo fault, a northwest-dipping normal fault which has been active throughout much of the late Quaternary.

This zone of normal slip and other northwest-dipping normal faults have transferred dextral slip from the Laguna Salada fault zone during the late Quaternary to several other oblique-dextral zones successively farther to the southwest. This connected series of northwest-striking oblique-dextral and northwest-dipping normal fault zones collectively forms a series of dilational right steps that are responsible for basin subsidence and pull-apart within Laguna Salada. Geomorphic evidence suggests that pull-apart was not continuous during this period and ceased at least once within the northern part of the Laguna Salada basin.

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## INTRODUCTION

The Sierra Cucapa lies astride the great structural depression of the Gulf of California tectonic province in the southwestern part of the Salton trough (Figure 1). This range contains many of the structural elements which have controlled

deformation in the trough since early in its history.

The well-exposed oblique-dextral and normal fault zones that bound the western margin of the Sierra Cucapa are directly responsible for the late Quaternary uplift of the range and the development of a deep elongate stepped basin in Laguna Salada (Biehler et al., 1964; Barnard, 1968;

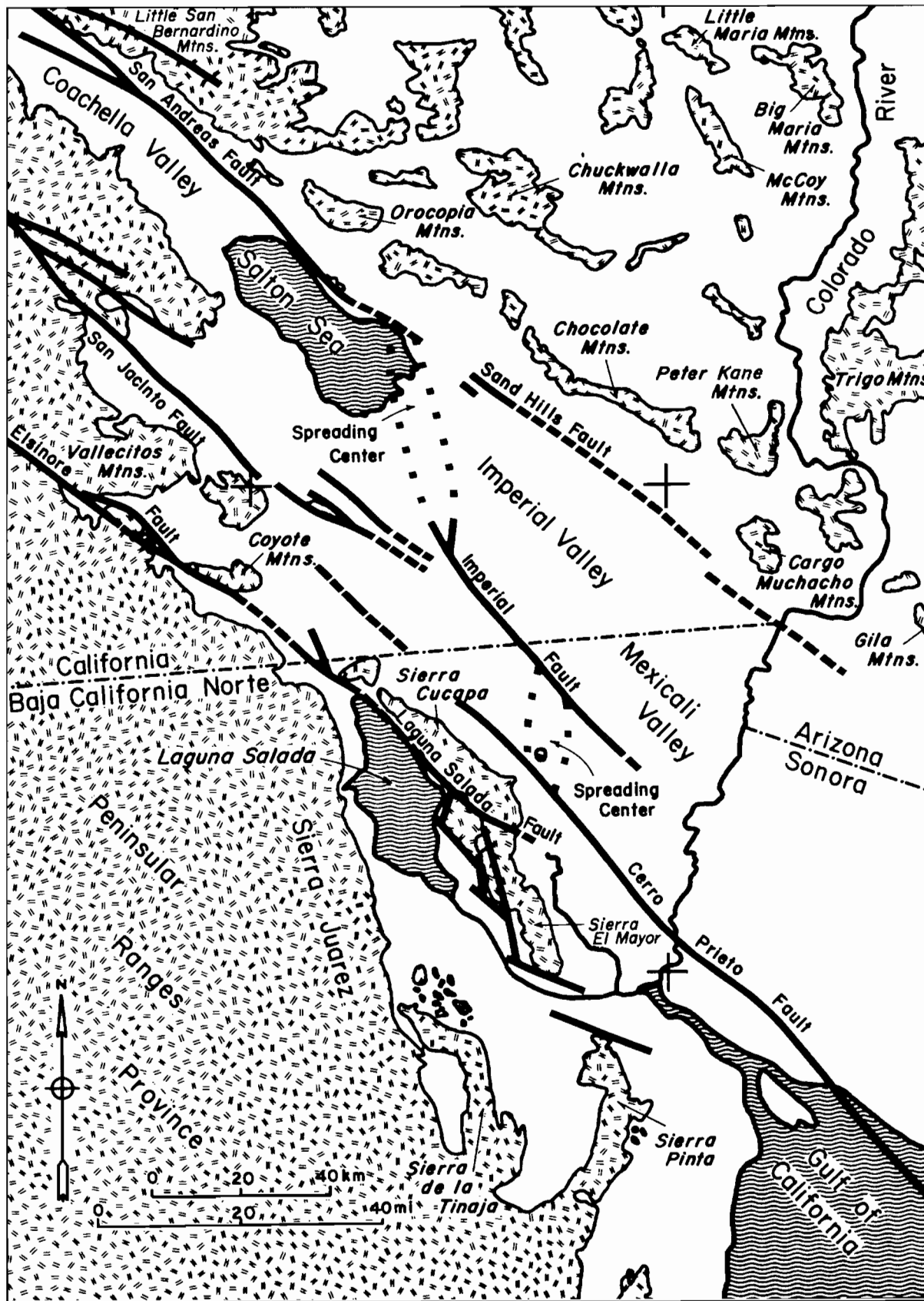


Figure 1—Map showing major structural and physiographic elements of the Salton trough. Note location of the Laguna Salada basin and the Sierra Cucapa along its southwestern margin.

Gastil, 1968; Kelm, 1971; Strand, 1980). The vertical relief of the basin and the rugged topography of the range are themselves products of even greater horizontal displacements along these faults.

The purpose of this chapter is to describe and discuss the sense and relative activity of faults exposed along the western margin of the Sierra Cucupa and their role in the development of the Laguna Salada basin. Field studies were concentrated on the western margin of the Sierra Cucupa along the central part of the Laguna Salada fault zone (Figure 2). Study was concentrated in this region because of the presence of many tectonic and geomorphic indicators of recent and historical fault movement such as fault scarps and instrumentally recorded earthquake epicenters (Barnard, 1968; Hileman et al., 1973; Strand, 1980). Large-scale mapping of displaced geologic and geomorphic surfaces was completed to evaluate the activity of individual fault strands within a northwest-trending 1-km-wide zone of deformation. The relative ages of faulted geomorphic surfaces was assessed by the degree of soil development present within them (Mueller, 1984). Rates of soil development, and therefore approximate absolute ages of the soils in the chronosequence, were estimated by comparison with other well-dated soil chronosequences formed in climatic environments similar to the southwestern Salton trough (Gile et al., 1960; Gile and Grossman, 1968; Gile, 1975; Bischoff et al., 1976; Schlemmon, 1976; Schlemmon and Purcell, 1976; Alexander and Nettleton, 1977). Also, the timing of a dated climatic change at the end of the Pleistocene some 7800–12,000 y.b.p. (years before the present) was used to estimate the maximum age of the Holocene soils (Wells, 1976; Van Devender, 1977; Burrows, 1979; Galloway 1983). Holocene soils were differentiated from Pleistocene soils by their various pedogenic characteristics, which are related to a change in the depth of soil wetting.

## PREVIOUS INVESTIGATIONS

Early workers in the Laguna Salada basin and the Sierra Cucupa quickly recognized the presence and/or recency of faulting exposed there (Lindgren, 1888; Beal, 1948; Gastil, 1968; Gastil et al., 1971). Later geophysical surveys by Kovach et al. (1962) and Biehler et al. (1964) contributed to an understanding of the region by using gravity surveys to develop models of the configuration of basin fill and underlying crustal characteristics. A more comprehensive gravity and magnetic study by Kelm (1971) further defined the shape and structure of the northern two-thirds of the basin. Sedimentological and stratigraphic studies (Dibblee, 1954; Walker, 1967; Walker, et al., 1967) provided data on gross stratigraphic sequences along the margins of the basin and on diagenetic alteration within them.

Work in the Sierra Cucupa (Barnard, 1968) included reconnaissance mapping of fault zones and intervening rock types, which outlined a structural and geologic history of the range. Studies of historic seismicity (Hileman, et al., 1973; Fuis, et al., 1977; Mike Reichle, oral communication, 1984) estimated epicentral locations of instrumentally recorded earthquakes in the area. Research into earlier historical earthquake accounts concluded that a major (magnitude >7.0) earthquake occurred along the Laguna Salada fault zone on February 23, 1892 (Strand, 1980).

## GEOLOGIC AND TECTONIC SETTING

Deformation within the Salton trough during the late Tertiary and Quaternary has been in response to transcur-

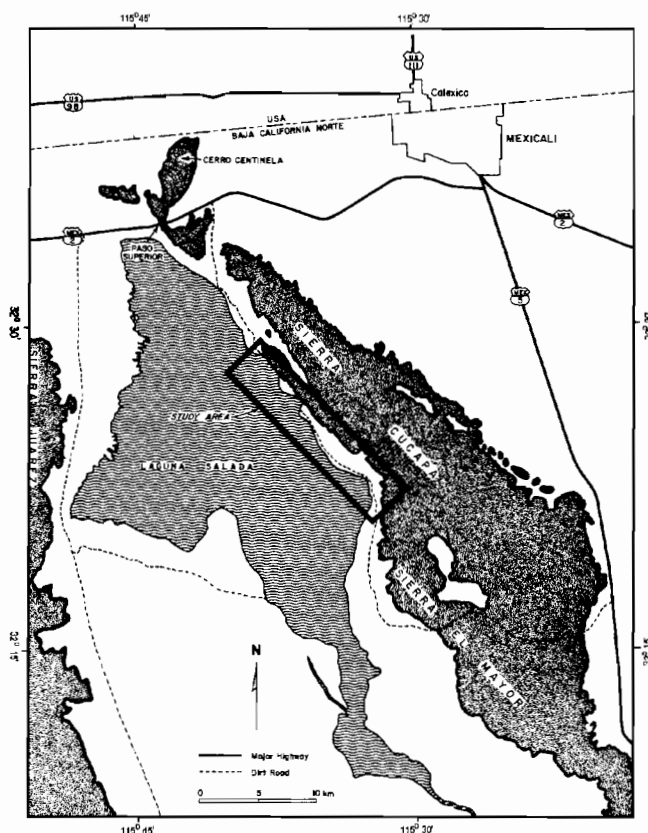


Figure 2—Diagram showing location of the detailed study area (Figure 4) along the southwestern margin of the Sierra Cucupa.

rent and divergent motion between the Pacific and North American plates (Elders and Biehler, 1975; Crowell and Sylvester, 1979; Sharp, 1982). Divergence, or rifting, has caused crustal attenuation, normal faulting, volcanism, and increased heat flow along the northwest-trending axis of the trough (Gastil, 1968; Muffler and White, 1969; Elders et al., 1972; Elders and Biehler, 1975; Robinson et al., 1976; Brown, 1978; Gastil et al., 1979). Transcurrent plate motion has led to major lateral displacements along northwest-striking dextral fault zones (Crowell, 1952, 1962, 1975; Allen, 1957; Sharp, 1967, 1981; Clark, 1972; Clark, et al., 1972).

The Sierra Cucupa consists of a series of tectonic slices of igneous, metamorphic, and sedimentary rocks separated by major oblique-dextral and normal fault zones (Barnard, 1968; Gastil et al., 1971). The oldest units in the study area are Paleozoic(?) prebatholithic metamorphic rocks consisting mostly of well-banded, coarse-grained quartzofeldspathic gneiss and marble. Lesser amounts of biotite-rich schist, amphibolite, and quartzite are also present (Barnard, 1968). All these units were intruded during the Mesozoic by plutonic rocks of the Peninsular Ranges province (Barnard, 1968; Gastil et al., 1971). The plutonic rocks are coarse-grained biotite tonalite and leucocratic granodiorite.

These pre-Cenozoic igneous and metamorphic rocks have in turn been partially overlain and/or intruded by Miocene volcanic units consisting of autobreccia flows and dikes. Pliocene and younger sedimentary units are exposed within and along the margins of the Sierra Cucupa and make up the bulk of basin fill within Laguna Salada (Dibblee, 1954; Curtis, 1963; Walker, 1967; Walker et al., 1967; Barnard, 1968).

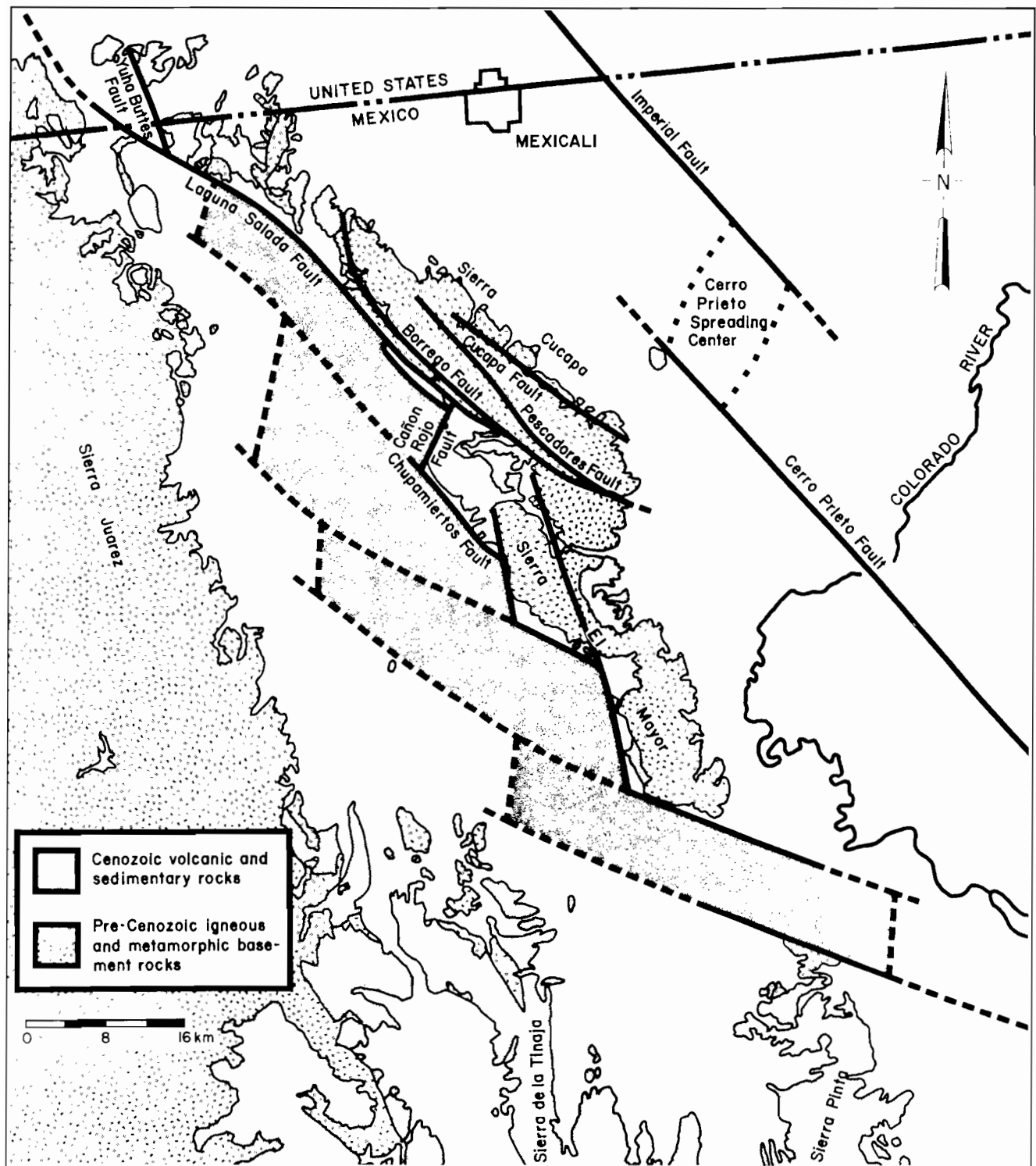


Figure 3—Diagram showing simplified area of basin fill (stippled region) in the Laguna Salada basin, which is related to pull-apart between oblique-dextral faults presently visible along the western margins of the Sierra Cucapa and Sierra Mayor. Modified from Lomnitz et al. 1970; Gastil et al., 1971; Kelm, 1971.

Deposition of these sediments into Laguna Salada has been dependent on (1) Pliocene shallow marine incursions from the Gulf of California; (2) the position of the Pleistocene Colorado River delta; and (3) continued localized, variable uplift of the ranges that define the edges of the basin (Dibblee, 1954; Walker, 1967; Barnard, 1968). More

importantly, deposition in Laguna Salada is controlled by subsidence of the basin itself.

Downwarping and attenuation of the crust underlying Laguna Salada has been generated by pull-apart between en echelon, northwest-striking oblique-dextral fault zones. Ongoing extension or pull-apart between the right-stepping



see MUELLER and ROCKWELL: Late Quaternary structural evolution of the western margin of the Sierra Cucapa, Baja California Norte (this volume).

Quaternary	Holocene	Qp	Historic playa lake sediments
		Qf1 Q11	Very poorly developed Typic Torrifluents; historic, active alluvial fan (f) and stream terrace (t) deposits; no visible soil development or horizonation, although calcareous
		Qf2 Q12	Moderately developed Typic Torrifluents; latest Holocene and historic (?) alluvial fan (f) and stream terrace (t) deposits; soils consist of thin, very poorly developed A-C profiles
		Qf3 Q13	Poorly to moderately developed Typic Camborthids; late-Holocene alluvial fan (f) and stream terrace (t) deposits; soils have incipient, poorly developed Bca horizons separating Avca and Cca horizons
		Qf4 Q14	Poorly developed Arenic Haplargids; early and mid-Holocene alluvial fan (f) and stream terrace (t) deposits; soils have partially engulfed Avca horizons and poorly to moderately developed Btca and Cca horizons; (CaCO <sub>3</sub> , NaCl, CaSO <sub>4</sub> ) locally common and are contained in the upper 70cm of soil profiles; geomorphic surfaces have a poorly developed desert pavement in regions with accelerated salt weathering
Pleistocene		Qf5 Q15	Moderately to well developed Arenic Haplargids; latest Pleistocene alluvial fan (f) and lake terrace (t) deposits; soils have thin Avca horizons which have been partially engulfed by underlying well-developed Btca horizons; soil profiles also have transitional BCca and Cca horizons; salts (CaCO <sub>3</sub> , NaCl, CaSO <sub>4</sub> ) common to several meters depth, although concentrations occur in uppermost meter; geomorphic surfaces have a poorly to moderately well developed desert pavement
		Qoa	Late Pleistocene alluvial fan deposits (appear similar to younger alluvium except better lithified)
Tertiary	Pliocene	Qc	Mid-Pleistocene alluvial fan deposits (have higher degree of intrastratal reddening and cementation in comparison with younger alluvial fan deposits)
		Pi	Imperial Formation (claystone and sandstone), uppermost portion of section south of Cañon Rojo fault zone may be in part Pleistocene Palm Spring Formation
Jur. Cret.		Kmgd	Cucapas granodiorite
		JKt	La Puerta tonalite
Unknown		Ms	Prebatholithic metasedimentary rocks

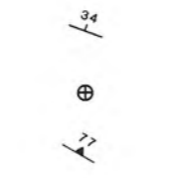
Note: Subscripts for Q1 through Q5 deposits include + and - (ie Q13-) signifying geomorphic surfaces respectively containing an especially well or poorly developed soil of a given type. Also, a,b,c...(ie Q14b) respectively denotes adjacent stream terraces containing a given soil type which increase in elevation and age.



Fault in/or bounding bedrock: dotted where covered, dashed where inferred; dip of exposed fault surface and trend and plunge of striations or mullions given where visible; bedrock (BFS) fault surface exposed during recent groundbreaking seismic event; vertical displacement in meters (3m).

Fault scarp in alluvial deposits: dotted where covered, dashed where inferred; 1. total (8m) vertical displacement in meters; 2. free face (4mFF) created during most recent groundbreaking seismic event, vertical displacement in meters; 3. multiple scarps, individual offset in meters

Contact: solid where well located or exposed; dashed where approximate or inferred, queried where uncertain



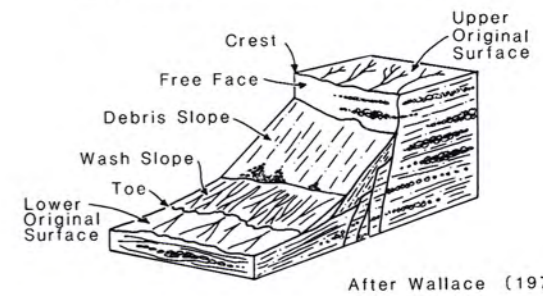
34 Strike and dip of bedding

⊕ Flat bedding

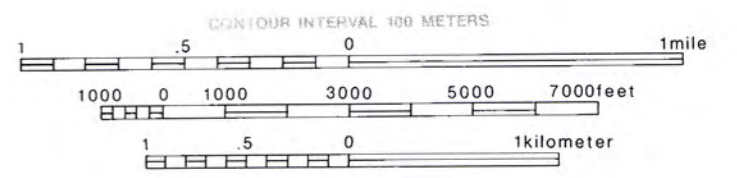
⊙ Foliation of fault zone rocks

- BS Beheaded stream
- LAS-3 Large antecedent stream (referenced in text)
- DOCW-3m Dextrally offset stream channel wall, offset in meters
- DS-25m Deflected stream channel, offset in meters

Morphology of an Alluvial Fault Scarp



After Wallace (1977)



faults has resulted in northeast striking normal faults which connect the northwest-striking dextral faults, collectively forming a series of dilational right steps. These have created four northwest-oriented, en echelon subbasins which define the deep sedimentary fill in Laguna Salada (Figure 3).

Basins or uplifted areas therefore depend on the geometry and interactions of major lateral faults and are usually localized along steps or bends in fault trends (Crowell, 1974a, b; Dibblee, 1977; Crowell and Baca, 1979; Fuis et al., 1982, 1984). Uplift of the Sierra Cucapa has resulted from the complex interactions of a number of major oblique-dextral fault zones. South of Mexican Highway 2, these include strands of the Cerro Prieto, Cucapa, Pescadores, Borrego, and Laguna Salada faults (Figure 3); (Barnard, 1968; Gastil, 1968).

Although the geomorphic expression of these faults indicates that the level of activity on them has varied during the Quaternary (Barnard, 1968; Mueller, 1984), long-term interactions in a transpressive environment (Sylvester and Smith, 1976) have created crowding and subsequent uplift of intervening crustal slices. Uplift of fault slices is greatest where two bounding zones of oblique-dextral slip converge toward the southeast (Crowell, 1974a; Dibblee, 1977), as is particularly the case between the Pescadores, Cascabel, Borrego, and Laguna Salada faults (Figure 3). Although southeasterly divergence is noted between the Cucapa and Pescadores faults, uplift of the area between them may instead be created by interactions between the southeasterly converging Pescadores and Cerro Prieto faults. Also, the Cucapa fault does not appear to have been very active during the late Quaternary based on the relative lack of geomorphic indicators of active faulting; therefore, its effect on the recent uplift of the range is assumed to be negligible.

The strong northwesterly trend of oblique-dextral fault zones in the Sierra Cucapa turns in the northern third of the range near Cerro Centinela to more northerly and northeasterly directions (Figure 3) (Barnard, 1968; Gastil, 1968). It is difficult at present to explain this divergence from regional strike, although it appears evident from sedimentological evidence (Barnard, 1968) that the northwestern quarter of the range has been intermittently uplifted throughout the Quaternary, possibly in a transpressive environment. The sense of slip on the fault zones bounding rapidly uplifted blocks in this area is presently unknown. Based on their present orientation, however, they may be oblique-sinistral and conjugate to the dominant, northwest-trending dextral faults. Alternatively, these presently northeast-trending faults may have once been northwest-trending dextral or north-trending normal faults within a block that has been rotated clockwise by simple shear between two bounding dextral-slip faults. These bounding dextral fault zones may have been the northern Laguna Salada fault and another less well defined fault zone adjacent to the northeastern margin of the Sierra Cucapa.

## LAGUNA SALADA FAULT ZONE

The central, southwestern margin of the Sierra Cucapa provides an excellent opportunity to evaluate the geometry and near-surface interactions of deformation within a major oblique-dextral fault zone. This area is doubly important because the zone of deformation bounds a deep, narrow, elongate stepped basin whose development appears to be

directly linked to movement on the Laguna Salada and related faults (Figure 3). Detailed mapping of these faults, and the geomorphic surfaces they have offset, as well as the development of a soil chronosequence, has led to a better understanding of the spatial and temporal constraints of slip along individual fault strands. Several important factors concern this diastrophism and need to be addressed, including (1) a description of exposed fault geometries; (2) their possible relationship to deeper crustal fault zones; and (3) the period of time during which they were active. For descriptive purposes, the mouth of each large antecedent stream canyon which cuts the horst formed between the Laguna Salada and Borrego faults is labeled LAS 1 through 7, beginning at the northwestern end of the field area (Figure 4).

The northern third of the Laguna Salada fault in the study area is directly exposed at the base of the crystalline range front and is covered, in part, by lake waters north and south of the large solitary alluvial fan formed by streams 1 and 2. This section of the fault zone is marked by a single straight fault trace with a consistent southwesterly dip of 55° to 60° (Figure 4).

The remarkable linearity of this single fault strand is broken slightly by a gentle left step several hundred meters north of stream 1 (Figure 4). This single fault strand has been highly active throughout the late Quaternary and appears to have defined the steep eastern wall of the Laguna Salada basin throughout this time interval.

The simple, straightforward geometry of the range-bounding strand begins to change at stream 3 (Figure 4). Here the surficial geometry of the fault plane steepens to a near vertical orientation. As the fault strand extends to the southeast, its surficial dip direction changes twice, from southwest to northeast and back, suggesting that the fault probably aligns with an approximately vertical zone at depth. Also, southeast of stream 3, this northeastern strand is contained within crystalline rocks of the Sierra Cucapa and has only minor structural relief across it. Based on its geometry, the lack of structural relief across it, and laterally deflected streams, this strand has probably had a predominantly lateral sense of slip during the latest Tertiary and Quaternary. Little Holocene offset seems to have occurred on this strand southeast of stream 3, except for very minor (1 m) downward slippage toward the northeast (Figure 4).

Several hundred meters northwest of stream 3, two large alluvial fault scarps splay off the range-bounding fault strand at a sharp obtuse angle (Figure 4). Southeast of this juncture, latest Pleistocene and Holocene activity along the Laguna Salada fault zone steps to the southwest and is localized along an intermittently preserved line of fault scarps offsetting Holocene alluvial fans. The alluvial scarps strike northeast where they join the range-bounding fault zone and begin to strike northerly and northwesterly as they extend southeastward down the range front. The more northeasterly of the two alluvial scarps extends down the length of the range front until it intersects the Cañon Rojo fault zone; the other scarp extends only about 2.5 km southeast of its intersection with the main range-bounding fault zone (Figure 4). This latter alluvial fault scarp decreases in height to the southeast and appears to die out completely; it does not appear to be simply covered by latest Holocene and historical alluvial deposits (Figure 4).

Minor scarplets offsetting early and middle Holocene alluvial deposits are visible northwest of stream 3 at the

Figure 4—Neotectonic map of the Laguna Salada and Cañon Rojo fault zones (see foldout).

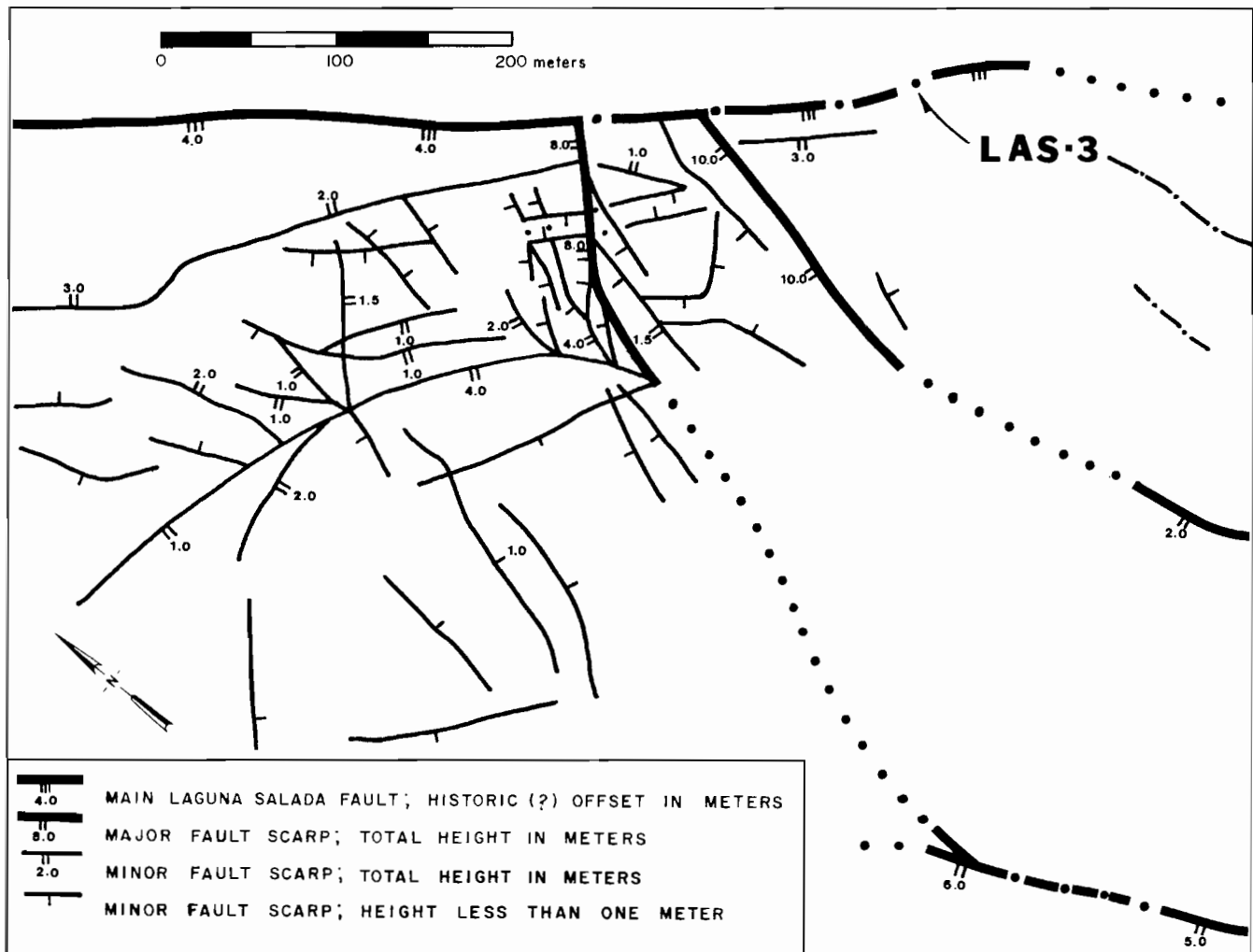


Figure 5—Field sketch of complex faulting offsetting Holocene alluvial deposits adjacent to a releasing right step in the Laguna Salada fault zone (at LAS-3 on Figure 4).

alluvial scarp/range-bounding strand intersection (Figure 5). They appear to have been formed by imperfect transfer of slip across this releasing fault step. Another important aspect of deformation at this releasing or dilational corner includes backtilting of geomorphic surfaces between the two northeast-striking alluvial scarps, possibly indicating that they are listric. Also, the vertical rate of slip across these north- to northeast-striking, predominantly normal faults during the Holocene is probably greater than along the connected northwest-striking oblique-dextral scarps farther to the southeast. This seems to indicate that extension and stratal rotation are greatest along northeast-striking normal faults, perpendicular to the length of the basin.

The eastern limit of thick late Quaternary sedimentary fill in the Laguna Salada basin is probably defined by the single main fault trace northwest of stream 3 and by the intermittently preserved, southwesternmost line of alluvial fault scarps offsetting Holocene geomorphic surfaces southeast of stream 3 (Figure 4). These scarps, which offset alluvial deposits, represent the locus of oblique-dextral slip across the width of the fault zone throughout at least the late Quaternary. A record of continued vertical offset across these scarps is visible as a series of progressively offset geomorphic surfaces of increasing late Quaternary age (Figure

4). The morphology of many of these composite scarps attests to the recency of offset along them (Wallace, 1977; Bucknam and Anderson, 1979); vertical alluvial free faces in loose historical and latest Holocene alluvium are preserved along much of their length (Figure 4) and may have been created by a large-magnitude earthquake on February 23, 1892 (Strand, 1980). At present there are no known temporally constrained geomorphic indicators of a lateral component of slip along these scarps (Mueller, 1984); recognition of offset stream-channel walls and deflected streams is blurred by the large vertical component of slip. Good geomorphic indicators of lateral slip, such as offset walls of stream channels, are generally not present because incision occurs only on the upthrown block, and rapid burial and deposition predominate on the downthrown block. The geometry of the scarps in relation to the Cañon Rojo fault, along with easily identifiable linear kinematic indicators visible on the recently exposed Laguna Salada fault surface near its juncture with the Cañon Rojo fault, indicate that the ratio of vertical to horizontal slip along the Laguna Salada fault during the Holocene has been about 1.4:1 (Figure 6).

Although the present level of exposure indicates only two obvious fault strands southeast of stream 3, evidence of a number of others was found in channels incised into Pleis-

tocene fan deposits (Figure 4). Here, individual slices of underlying igneous rocks and bounding gouge zones provided compelling evidence of the penetrative aspect of deformation across the zone. The 1-km width of the Laguna Salada fault zone thus contains many individual fault strands, whose periods of activity have varied since the inception of the zone.

The oblique-dextral line of fault scarps offsetting late Quaternary alluvial deposits is terminated abruptly about 10 km southeast of its intersection with the range-bounding fault strand at stream 3 (Figure 4). This termination marks its intersection with the northeast-striking normal faults of the Cañon Rojo fault zone. Striations on the bedrock fault surface of the Cañon Rojo fault, exposed during the 1892 earthquake, have 90° rakes that indicate the purely normal sense of slip along that fault (Figure 6). An inactive extension of the Cañon Rojo fault zone extends another 600 m to the northeast, where it abuts the now inactive, predominantly strike-slip northeastern strand of the Laguna Salada fault zone (Figure 4). Offset alluvial deposits across this short 600-m section of the Cañon Rojo fault zone indicate no more than 140 m of slip since the middle Pleistocene. The mullions and striations, visible on the active oblique-dextral Laguna Salada fault and the normal Cañon Rojo fault strand, respectively, and the line formed by their intersection are all essentially identical in orientation (Figure 6). This then gives a good representation of the late Quaternary direction or slip vector of pull-apart in this part of the Laguna Salada basin. It also indicates the simple transferral of dextral slip from the Laguna Salada fault across the Cañon Rojo fault to the oblique-dextral Chupamieros fault lying to the southwest (Figure 3).

The morphology of the fault scarps defining the corner formed by the oblique-dextral Laguna Salada and normal Cañon Rojo faults indicates that the most recent, possibly historical seismic event ruptured around it and extended approximately 2.5 km to the southwest along the Cañon Rojo fault (Figure 4). This geometry is consistent with other active dilational fault jogs within the Salton trough which indicate that rupture propagation during seismic events is impeded at corners created at fault steps (Sibson, 1986).

## SOIL STRATIGRAPHY AND SLIP-RATE ESTIMATES

Holocene and Pleistocene soils can be separated based on their morphological and chemical characteristics, related to variations in the soil-forming environment or climate during the late Quaternary. Alluvium isolated from further deposition since the end of the Pleistocene contains soils corresponding to the more arid Holocene climate. Because the Holocene soils at Laguna Salada tend to be an order of magnitude thinner than the Pleistocene soils, they can easily be differentiated in the field. The time of this change in climate ranges from 7800-12,000 y.b.p., based on packrat midden data from the Sonoran and Mojave deserts (Wells, 1976; Van Devender, 1977; Burrows, 1979; Galloway, 1983). Because of the lack of radiocarbon dates for this chronosequence, the precise determination of the age of individual Holocene fans cannot be determined; the slip-rate estimates, which are based on maximum ages, are therefore minimum rates.

The vertical rate of slip along the Laguna Salada fault zone is greatest where individual strands are oriented normal to the northwest-southeast extensional axis of the basin. The largest recorded scarps, located several hundred meters northwest of stream 3, display a minimum Holocene offset

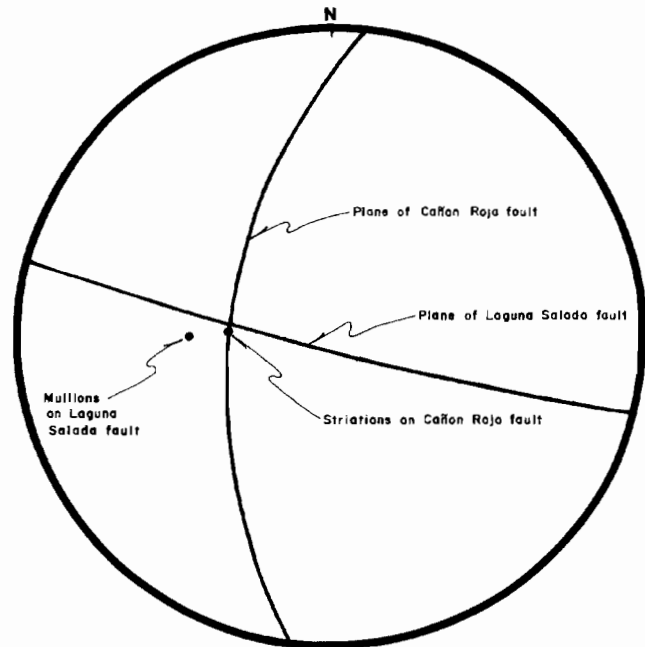


Figure 6—Stereoplot of fault surfaces and associated striations and mullions exposed at the intersection of the active strands of the Laguna Salada and Cañon Rojo faults.

of 18 m and thus a minimum vertical slip rate of 1.5 to 2.3 mm/yr. Calculation of the lateral slip rate along the fault zone is not well defined because the high vertical component of slip accelerates erosion of stream terrace and alluvial fan edges, or geomorphic piercing points. However, because the direction of Holocene slip at the junction of the Laguna Salada and Cañon Rojo faults is well defined, the minimum lateral slip rate along the active Laguna Salada strand can be inferred based on the measured vertical displacement. Thus, the minimum lateral rate of Holocene slip along this strand 1.7 km northwest of the Cañon Rojo fault is  $0.70 \pm 0.15$  mm/yr based on 9.0 m of vertical displacement and a slip vector of 54°, N84°W. The corresponding minimum vertical slip rate at this point is  $1.0 \pm 0.2$  mm/yr. It should be emphasized that the calculated slip rates are minimum rather than absolute values; offset geomorphic surfaces may actually be as much as several times younger than the single 7800-12,000 y.b.p. age constraint.

## BASIN DEVELOPMENT

Basin development within Laguna Salada appears to be closely related to the active oblique-dextral and normal fault zones exposed along the western margins of the Sierra Cucapa and Sierra El Mayor. Kelm (1971), using gravity studies based on closely spaced data (Figure 7), concluded that these faults define the very steep northeastern walls of the basin. The southwestern side of the basin appears to have had a similar origin; however, the faults defining it have no surficial representation because of repeated late Holocene inundation, except for faults farther to the south, which define the northern end of the Sierra Pinta (Gastil, 1968; McEldowney, 1970).

The sense of slip on these bounding fault zones and the geophysically inferred shape of deep sedimentary fill in



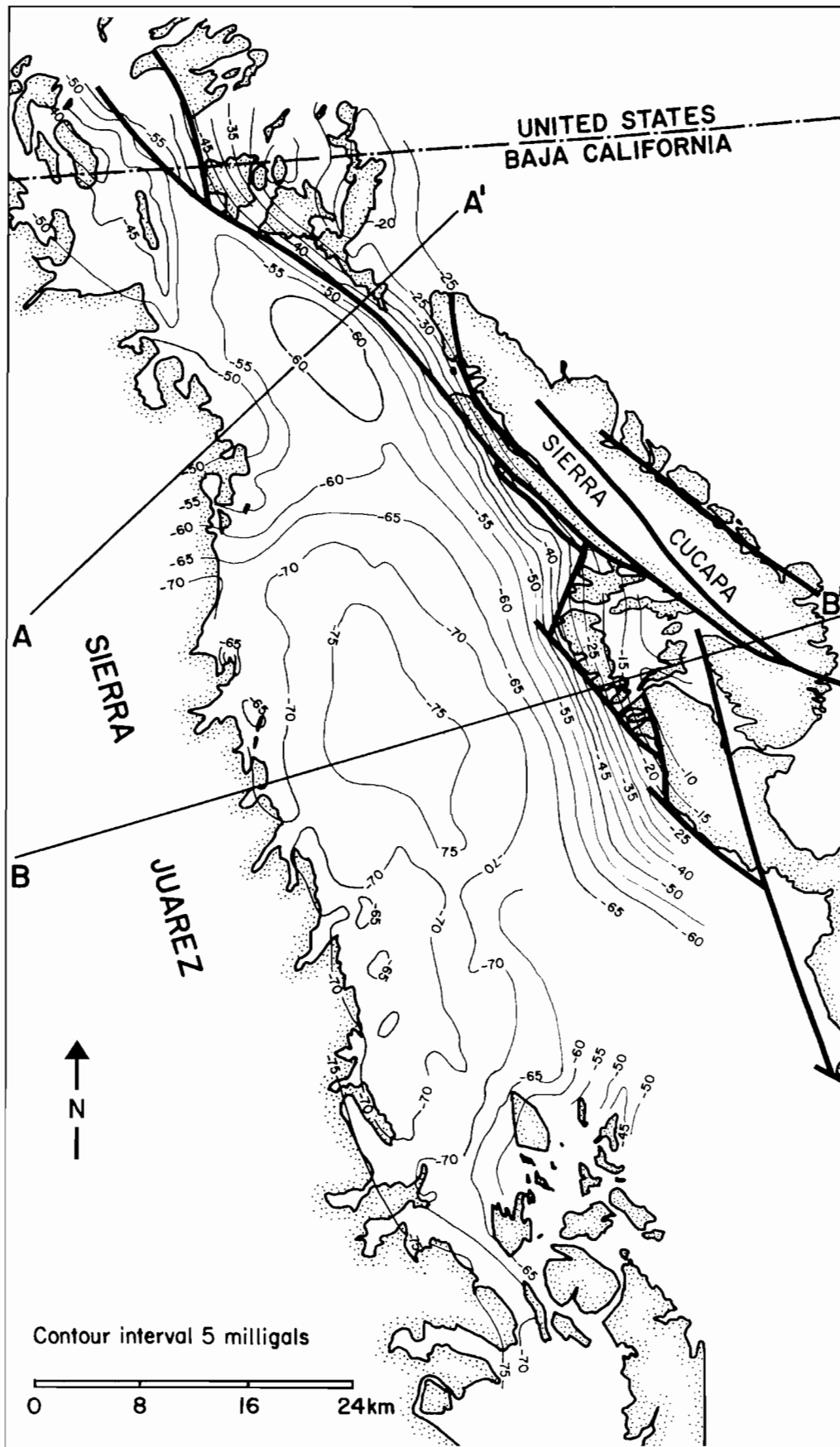


Figure 7—Gravity map showing an echelon gravity lows in the Laguna Salada basin (after Kelm, 1971).

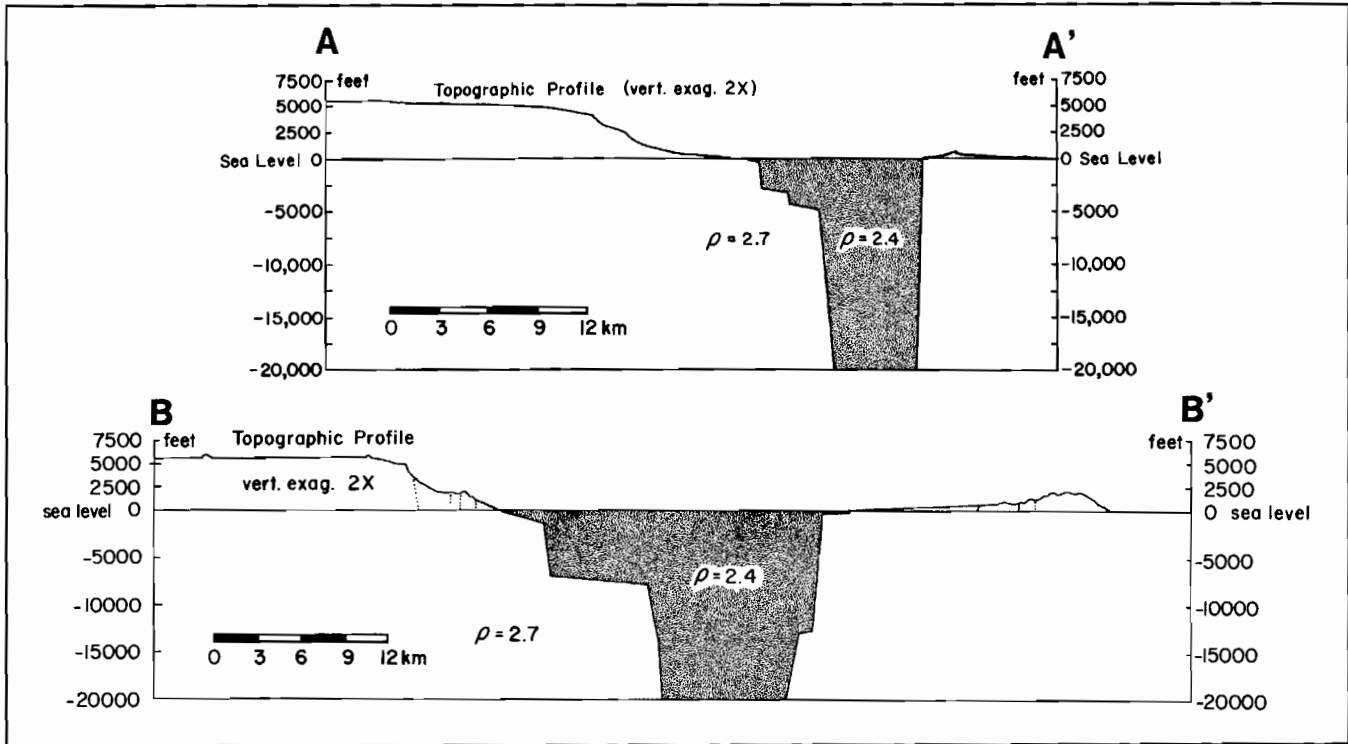


Figure 8—A-A' is cross section (from Kelm, 1971) showing basin shape derived from gravity data in the northern Laguna Salada basin. B-B' is cross section (from Kelm, 1971) showing basin shape derived from gravity data in the central Laguna Salada basin (section cuts across two coalesced pull-aparts; see Figure 7 for section locations). These cross sections derived from gravity surveys provide only a gross picture of basin shape. Additional subsurface data should provide a more detailed picture of basin gravity, itself a product of complex, long-term fault interactions along the Laguna Salada eastern margin.

Laguna Salada suggest that the basin was created by extension or pull-apart between right-stepping oblique-dextral fault zones (Figure 7). Four individual subbasins apparently coalesced as a result of ongoing strike-slip and formed a single basin, which was surficially continuous during at least the late Quaternary.

Geophysical data indicate that the depth of sedimentary fill within the northernmost subbasin is probably more than 5 km (Figure 8, A-A') (Kovach et al., 1962; Biehler et al., 1964; Kelm, 1971). Fill within the other three pull-aparts differs (based on gravity data) and may be due to either variable amounts of extension within individual subbasins or to the specific manner in which extension was accommodated (Figure 8, B-B'). Based on the deep and elongate, highly evolved shape of individual subbasins (Mann et al., 1983) the cumulative amount of dextral slip along the northwest-striking oblique-dextral faults is possibly on the order of several tens of kilometers.

Although little is known about the early development of the Laguna Salada basin, the late Quaternary history of slip along its eastern margin is better constrained. Inferences can therefore be drawn about the late Quaternary basin development of this part of Laguna Salada based on the geomorphic evidence of faulting activity.

Latest Pleistocene and Holocene slip across the Laguna Salada fault zone indicates active pull-apart and basin subsidence centralized along the Cañon Rojo fault zone. This differs from previous ideas of pull-apart basin development which viewed extension as being localized in the center as opposed to one end of the basin (Crowell, 1974b; Mann et al., 1983). This style of faulting, however, has not been con-

stant throughout the late Quaternary. Extensive lacustrine terrace development across the footwall blocks of both fault zones (Figure 4) indicates a late(?) Pleistocene cessation in vertical uplift across both the Laguna Salada and Cañon Rojo faults. A substantial period of time is believed to have been required to cut these terraces, considering the material they cut across and their width. Cessation of vertical uplift may have been created by either a period of pure strike-slip along the Laguna Salada fault zone with little transferral of dextral slip across the Cañon Rojo fault to the Chupamieros fault (Figure 9); or by an extended seismic gap along the Laguna Salada fault.

Prior to the late Pleistocene, pull-apart was probably active for much of the Pliocene and early Pleistocene, based on the steep range front of the Sierra Cucapa, the depth of fill, and the length of the individual subbasins in Laguna Salada. Fault-generated petrofabrics exposed along some sections of the range-bounding fault zone north of stream 3 may have been created at an upper midcrustal level and thus also indicate a long history of oblique-dextral slip. Therefore, basin development appears to be intermittent and is dependent upon the rates and senses of slip along bounding oblique-dextral fault zones.

Considering the amount of extension required to form the coalesced pull-apart basins in Laguna Salada, underlying crust of continental (Peninsular Ranges province) affinity may have been thinned or attenuated. This may account for the extremely high heat flow in the basin, currently being defined by the drilling of geothermal exploration wells by the Mexican government. Laguna Salada therefore may be a precursor to the more highly evolved Imperial and

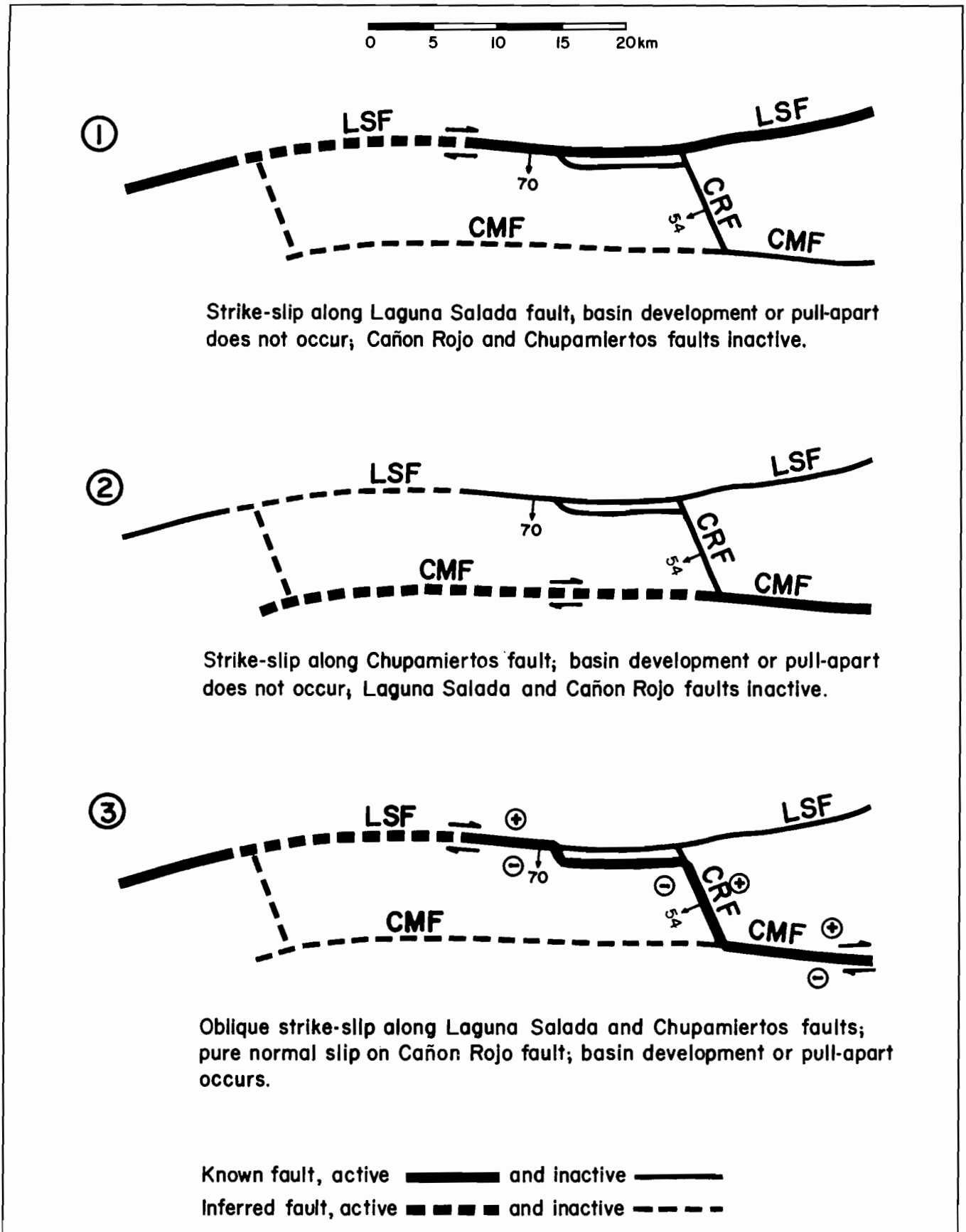


Figure 9—Diagram relating possible scenarios of faulting activity in the northernmost pull-apart and its effect on late Quaternary basin development in that section of Laguna Salada.

Mexicali valleys and may eventually experience enough crustal attenuation to initiate spreading and the formation of oceanic crust.

The evolution of Laguna Salada and its relationship to the Imperial and Mexicali valleys may provide insight into the ongoing deformation within the Gulf of California. Widening and development of the Salton Trough has isolated individual blocks of continental affinity including the Sierra Cucapa. Branching rifts or pull-aparts, such as the Mexicali Valley and Laguna Salada basin may therefore be an intrinsic part of rift development as widening oceanic crust captures or assimilates enclosed continental crust.

## CONCLUSIONS

The western margin of the Sierra Cucapa is bounded by active oblique-dextral faults of the Laguna Salada fault zone. The Laguna Salada fault has been repeatedly active during the Holocene; the most recent rupture probably occurred during the February 23, 1892 M7-7.5 earthquake. Active dextral faulting along only the Laguna Salada fault has not created subsidence or basin development in Laguna Salada. However, during simultaneous slip on the Laguna Salada, Cañon Rojo and related faults, basin formation occurs as dextral slip along the Laguna Salada fault zone is transferred southeastward to the head of the Gulf via a series of pull-apart basins. Geomorphic evidence suggests that basin formation was not continuous during the late Quaternary but ceased at least once within the northern part of the Laguna Salada basin. This may reflect changing distribution of Quaternary slip among faults within the zone, or it may reflect variations in the moderate to long-term slip rate of the system.

## ACKNOWLEDGMENTS

We thank Tom Pinault, Tammy Waid, Carl Clark, Dale Hall, Tina McKenzie, and the San Diego State University Quaternary geology class of 1983 for able and helpful assistance in the field. John Crowell and Gordon Gastil provided thoughtful and constructive reviews which supplemented our ideas and interpretations. Finally, we would like to thank Eric Frost for the use of the 4-wheel-drive vehicle for the duration of this study, Don Kent and Michael Huster for their contribution of boats and outboard motors, and Steve Troseth for redrafting the map in Figure 4.

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