JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. B6, PAGES 10,339–10,346, JUNE 10, 1991

Age Constraints for the Present Fault Configuration in the Imperial Valley, California: Evidence for Northwestward Propagation of the Gulf of California Rift System

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Releveling and other geophysical data for the Imperial Valley of southern California suggest the northern section of the Imperial-Brawley fault system, which includes the Mesquite Basin and Brawley Seismic Zone, is much younger than the age of the valley itself. A minimum age of 3000 years is calculated for the northern segment of the Imperial fault from correlations between surface topography and geodetically observed seismic/interseismic vertical movements. Calculation of a maximum age of 100,000 years is based upon displacements in the crystalline basement along the Imperial fault, inferred from seismic refraction surveys. This young age supports recent interpretations of heat flow measurements and the evolution of geothermal systems, which also suggest that the current patterns of seismicity and faulting in the Imperial Valley are not long lived. The current fault geometry and basement morphology suggest a northwestward growth of the Imperial fault and a northwestward migration of the Brawley Seismic Zone. If this localized process is representative of more regional tectonic processes along the extent of the Salton Trough, we suggest that this migration is a manifestation of the propagation of the Gulf of California rift system into the North American continent.

INTRODUCTION

The Salton Trough is a complex transition zone between crustal spreading in the Gulf of California and right-lateral transform motion along the San Andreas fault system (Figure 1). The Imperial Valley is that section of the Salton Trough north of the U.S.-Mexico border and south of the Salton Sea (Figure 2). The Trough is characterized by predominately right-stepping, right-lateral en echelon faults, presumably linked by zones of crustal extension [*Lomnitz et al.*, 1970; *Elders et al.*, 1972]. It forms a 150 by 300 km structural depression which is filled by up to 15 km of late Cenozoic sediments. The seismic velocity of the lower 5–10 km (V_p = 5.7 km/s) suggests these sediments are greenschist-facies, metasedimentary rocks [*Fuis et al.*, 1984]. The age of the Imperial Valley-Salton Trough region is suggested to be between 4 and 12 million years [*Larson et al.*, 1968; *Moore and Buffington*, 1968; *Ingle*, 1974].

The Imperial Valley and its major fault systems trend northwesterly, nearly parallel to the relative motion between the North American and Pacific plates. Dextral faulting predominates, although northeast-trending sinistral structures, as well as dip-slip motion along north-south surface breaks, play a significant role in the regional tectonics [*Johnson and Hutton*, 1982; *Nicholson et al.*, 1986; *Reilinger and Larsen*, 1986].

The Mesquite Basin is a subaerial topographic low bounded on the west by the northern Imperial fault and on the east by the Brawley fault (Figure 2). Maximum basin relief is about 10 m relative to its periphery. Evidence that the Mesquite Basin is actively subsiding includes geodetic measurements of surface deformation and measurements of vertical slip along the Imperial and Brawley faults. We provide evidence that the Mesquite Basin is extremely young compared to the age of the Imperial Valley, suggesting this section of the Imperial-Brawley fault system is at an early stage of tectonic development. We extend this hypothesis and suggest ongoing northwestward propagation of the Gulf of California rift system.

IMPERIAL VALLEY SEISMICITY AND FAULTING

The Imperial Valley is one of the most seismically active regions of California (Figure 3). A significant fraction of this seismicity occurs within the Brawley Seismic Zone, a region of high activity between the northern Imperial and southern San Andreas faults [*Johnson*, 1979; *Johnson and Hill*, 1982]. The Imperial fault ruptured historically in 1940 (M_L 6.4, M_S 7.1) and in 1979 (M_L 6.6, M_S 6.9); episodes of creep have been recognized along the fault since 1966 [*Allen et al.*, 1972]. The seismic moment of the 1979 earthquake is well determined (6×10^{25} dyn cm) [e.g., *Kanamori and Regan*, 1982], while that for the 1940 event ranges between 10 and 80×10^{25} dyn cm [*Trifunac and Brune*, 1970; *Hanks et al.*, 1975] although the 48×10^{25} dyn cm moment estimated from long-period surface waves is preferred [*Doser and Kanamori*, 1987]. Other major earthquakes in the Imperial Valley include the recent 1987 Superstition Hills earthquake sequence: a M_S 6.2 event produced by slip along a northeast-trending seismic lineament, followed 12 hours by a M_S 6.6 earthquake produced by slip along the Superstition Hills fault [*Magistrale et al.*, 1989; *Williams and Magistrale*, 1989].

The 1979 surfacial rupture of the Imperial fault extended from a point 5 km north of the border northwestward

Paper number 91JB00618.
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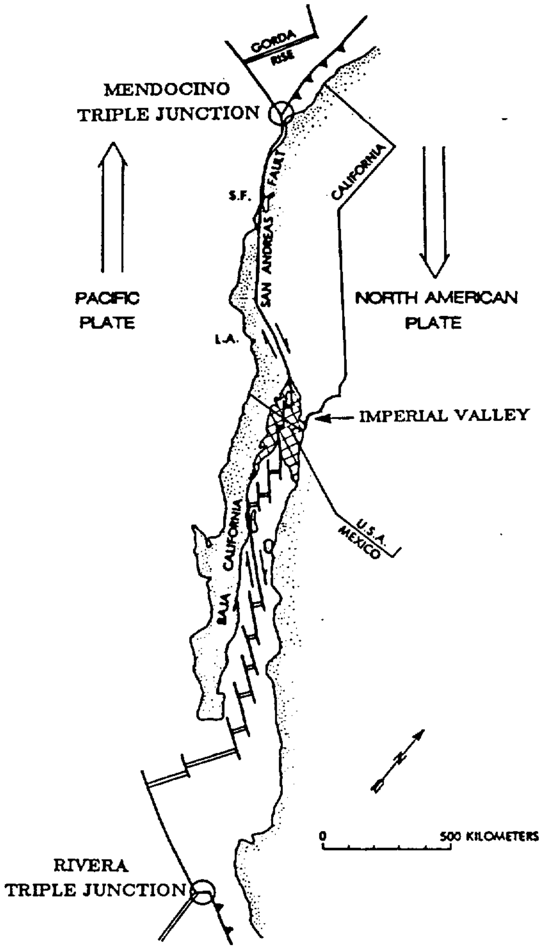

Fig. 1. The Salton Trough (hatch pattern) is a transition zone between crustal spreading in the Gulf of California and right-lateral transform motion along the San Andreas fault. The Imperial Valley is that portion of the Salton Trough north of the U.S.-Mexico border and south of the Salton Sea. Abbreviations are S.F., San Francisco; L.A., Los Angeles. Map modified from *Lachenbruch et al.* [1985].

33.1 km to a point south of Brawley (Figure 4). The predominate strike of the Imperial fault is N37° W. Along the northwestern most 5 km, however, the fault bends and trends north; we refer to this segment as the north extension. Trending parallel and lying 6 km east of the north extension, the Brawley fault ruptured in 1979 along a 13 km surface break. This rupture pattern generally featured left-stepping en echelon cracks that extended a few millimeters to a few centimeters [*Sharp et al.*, 1982]. A third, relatively minor 1 km north-trending break named the Rico fault was mapped 6–7 km east of the Brawley fault (Figure 4). The surface breakage along this structure resembled that of the Brawley fault zone. The geometrical similarity in strike and separation shown by the north extension, Brawley, and Rico faults, suggest a similar tectonic origin.

The epicenter of the 1940 earthquake was north of the U.S. border, but right-lateral surfacial offsets were larger in Mexico (Figure 3). A maximum surface offset of 6 meters was recorded near the border, with displacement tapering off rapidly to the north [*Trifunac and Brune*, 1970; *Sharp*, 1982]. Geodetic measurements indicate 4.5 and 3.0 m of right-lateral slip (coseismic plus postseismic) along the southern and northern halves of the Imperial fault, respectively (i.e., north and south of the epicenter), with 2.0 m postseismic slip along a northwest extension of the Brawley fault [*Reilinger*, 1984]. The 1979 epicenter was south of the border, although surfacial displacement was observed only in the United States. Maximum coseismic surfacial offset was 55–60 cm, with considerable afterslip (~ 30 cm) during the following 6 months [*Sharp et al.*, 1982]. Strong ground motion and geodetic modeling [*Archuleta*, 1984; *Hartzell and Heaton*, 1983; *Reilinger and Larsen*, 1986] suggest an average slip of about 1 m along the fault plane, with small patches of greater displacement (inferred to be asperities).

The mechanism of strain transfer between the Imperial and San Andreas faults within the Brawley Seismic Zone has been the focus of considerable investigation [e.g., *Johnson*, 1979]. A conjugate relationship of right-lateral, northwest-

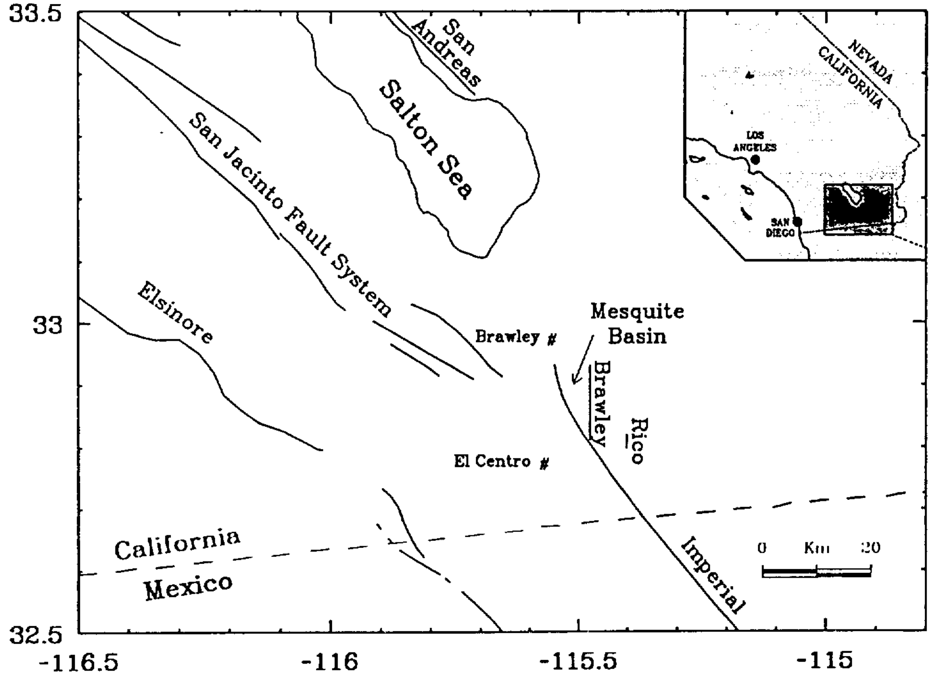

Fig. 2. The Imperial Valley and important faults. The Mesquite Basin is a subaerial topographic depression of about 10 m between the Imperial and Brawley faults.

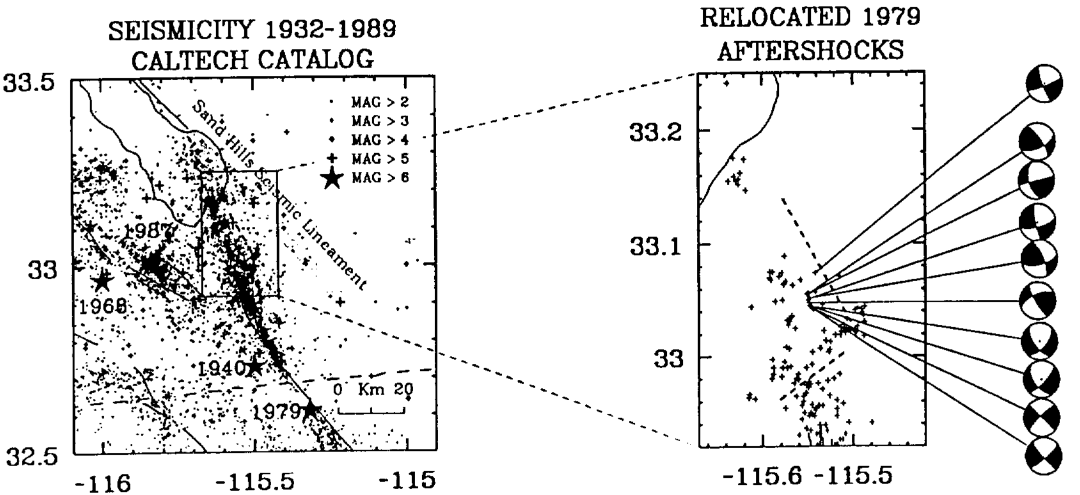

Fig. 3. Seismicity in the Imperial Valley between 1932 and 1989 (Caltech/USGS Catalog). Major events include the 1940 Imperial Valley (M_S 7.1), 1968 Borrego Mountain (M_L 6.5), 1979 Imperial Valley (M_S 6.6), and the 1987 Superstition Hills (M_S 6.6, M_S 6.2) earthquakes. The Brawley Seismic Zone is the active region between the northern reach of the Imperial fault and the southern extent of the San Andreas. The Sand Hills Seismic Lineament is shown by the shaded strip outlining earthquakes trending southeast from the southern end of the San Andreas fault. Shown in the inset are aftershocks of the 1979 earthquake which have been relocated following the methods outlined by *Doser and Kanamori* [1986]. The dashed lines represent orthogonal faults used to satisfy the observed vertical deformation from the 1979 event [*Reilinger and Larsen*, 1986]. Focal mechanisms (lower hemisphere, equal area projections [*Reasenberg and Oppenheimer*, 1985]) for events defining a northwest trend indicate right-lateral strike slip motion.

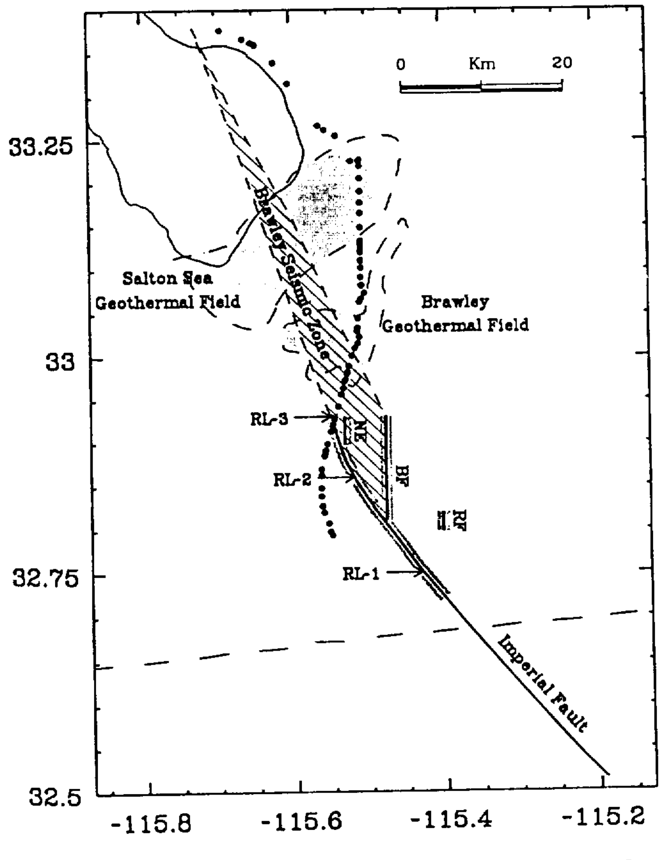

Fig. 4. Map of the Imperial Valley and important tectonic features. Abbreviations are RF, Rico fault; BF, Brawley fault; NE, North Extension. The shaded pattern along each fault indicates the surface rupture from the 1979 earthquake. The Brawley Seismic Zone (hatched) is the region of high seismicity extending northwest from the northern reach of the Imperial fault. The Salton Sea and Brawley geothermal fields are indicated by the shaded patterns. Refraction surveys [*Fuis et al.*, 1984] cross the Imperial fault at RL-1, RL-2, RL-3. The leveling route is shown by the series of dots from the central Imperial Valley to the eastern border of the Salton Sea (each dot representing a benchmark).

trending faults perpendicular to left-lateral, northeast-trending structures may play a significant role in the regional tectonics [*Nicholson et al.*, 1986]. Although the Imperial and San Andreas faults strike predominately northwest (right-lateral), a left-lateral structure extending northeast from the northern terminus of the Imperial fault is indicated from focal mechanisms and the aftershock pattern of the 1979 earthquake [*Johnson and Hutton*, 1982]. A conjugate fault mechanism is supported by *Reilinger and Larsen* [1986], who suggested several tectonic models of the Brawley Seismic Zone satisfying geodetically determined measurements of vertical surface displacement. The preferred model consists of a northeast-trending left-lateral fault conjugate to a right-lateral northwest-trending fault dipping 70° to the southwest (Figure 3, dashed lines). Neither fault broke the surface, but roughly 1 m of slip at depth is required to fit the geodetic measurements. A similar conjugate fault relationship was observed for the 1987 Superstition Hills earthquake sequence [e.g., *Magistrale et al.*, 1989].

Aftershocks from the 1979 earthquake have been relocated following the methods of *Doser and Kanamori* [1986] and *Klein* [1985] (Figure 3). The northeast-trending seismic lineament first identified by *Johnson and Hutton* [1982] is clearly defined. To the north, a tightly constrained group of events following a northwesterly direction is indicated. Epicentral depths for this cluster range from 5 to 11 km, possibly putting them on the 70° west-dipping structure suggested by *Reilinger and Larsen* [1986]. We have computed focal mechanisms for these events and find them consistent with a northwest-trending right-lateral fault (Figure 3). Thus, both seismic and geodetic data suggest the tectonic framework of the Brawley Seismic Zone is marked by en echelon northwest-trending right-lateral faults linked by conjugate left-lateral structures.

Extending southeast from the southern tip of the San Andreas fault is a linear alignment of earthquakes [e.g., *Johnson and Hutton*, 1982], here referred to as the Sand Hills Seismicity Lineament (Figure 3). This feature may signify the southeasterly extension of the San Andreas fault. Although there is no surfacial geological evidence to support this hypothesis [*Sharp*, 1982], creep is suggested along northwest segments of the Sand Hills lineament [*Jennings*, 1975].

The earthquake recurrence interval along the Imperial fault is not well constrained. *Sykes and Nishenko* [1984] use the 39 year interval separating the 1940 and 1979 shocks as well as a 1915 earthquake sequence located near El Centro [*Beal*, 1915] to estimate a 32 year recurrence rate. *Anderson and Bodin* [1987] suggest the fault north of the border will next rupture between 2010 and 2050 (50 year recurrence), and the next break along the southern segment to occur between 2170 and 2290 (300 year recurrence). Measurements of surface offset, as well as seismic and geodetically determined estimates of fault slip at depth, indicate the 1940 fault rupture was several times larger than in 1979, in agreement with the larger moment for the 1940 event. North of the border, however, the magnitude of horizontal surface displacement was relatively constant for the two earthquakes. One explanation for this is that the fault north of the border may rupture more frequently but with smaller events. Alternatively, the large postseismic slip following the 1940 earthquake indicated by geodetic data, suggests that a significant fraction of strain buildup may be relieved aseismically.

If the entire 49 mm/yr movement between the Pacific and North American plates predicted by new global plate models (NUVEL-1) [*DeMets et al.*, 1987, 1990] is accommodated across the Imperial fault, 1.0 m of seismic or aseismic fault slip would require a 20 year interval of strain buildup. More likely, however, a significant component of plate motion is distributed along the Elsinore and San Jacinto fault systems [*Sharp*, 1981; *Pinault and Rockwell*, 1984; *Snay et al.*, 1986], as well as faults off the coast of southern California [e.g., *Weldon and Humphreys*, 1986]. Trilateration and triangulation measurements from 1941 to 1987 in the central Imperial Valley indicate an average displacement across the Imperial fault of 35–43 mm/yr [*Prescott et al.*, 1987; *Snay and Drew*, 1988]. Preliminary results utilizing the Global Positioning System (GPS) suggest a slightly larger rate between 1986 and 1989, although interpretation of these measurements have been complicated by large displacements from the 1987 Superstition Hills earthquake sequence [*Larsen*, 1991].

Assuming 40 mm/yr of plate motion across the Imperial fault, 1.0 m of potential slip will accumulate in 25 years. This is equivalent to the earthquake recurrence interval, at least for the northern segment of the Imperial fault, if the ~ 1.0 m surface displacement measured in 1940 and 1979 is characteristic of fault displacement and if all slip is generated seismically. Considering the likelihood of aseismic deformation, as well as seismic and geodetic models indicating 2–3 m slip asperities along the 1979 rupture plane, it is reasonable to expect that the average slip generated along the northern Imperial fault during each earthquake cycle is somewhat greater than 1.0 m. Assuming 2–3 m of slip (based on the seismic plus postseismic offset estimated for the 1940 earthquake and the maximum slip observed for the 1979 earthquake), more reasonable estimates of earthquake recurrence would be 50 to 75 years for this segment of the Imperial fault.

SUBSIDENCE OF THE MESQUITE BASIN

First-order leveling surveys crossing the northern Mesquite Basin were conducted by the National Geodetic Survey (NGS) in 1931, 1941, 1974, 1978, and 1980 (Figure 4). Profiles of elevation change from 1931 to 1941, 1941 to 1974, and 1978 to 1980 are shown in Figure 5. The procedure used to determine these crustal movement profiles is described in *Brown and Oliver* [1976]. Briefly, an estimate of relative elevation change between successive benchmarks is obtained by subtracting the elevation difference between benchmarks measured at some reference time from the difference measured at some later time. These movement profiles have not been connected to any external reference. Therefore, only relative movements along the level lines are significant.

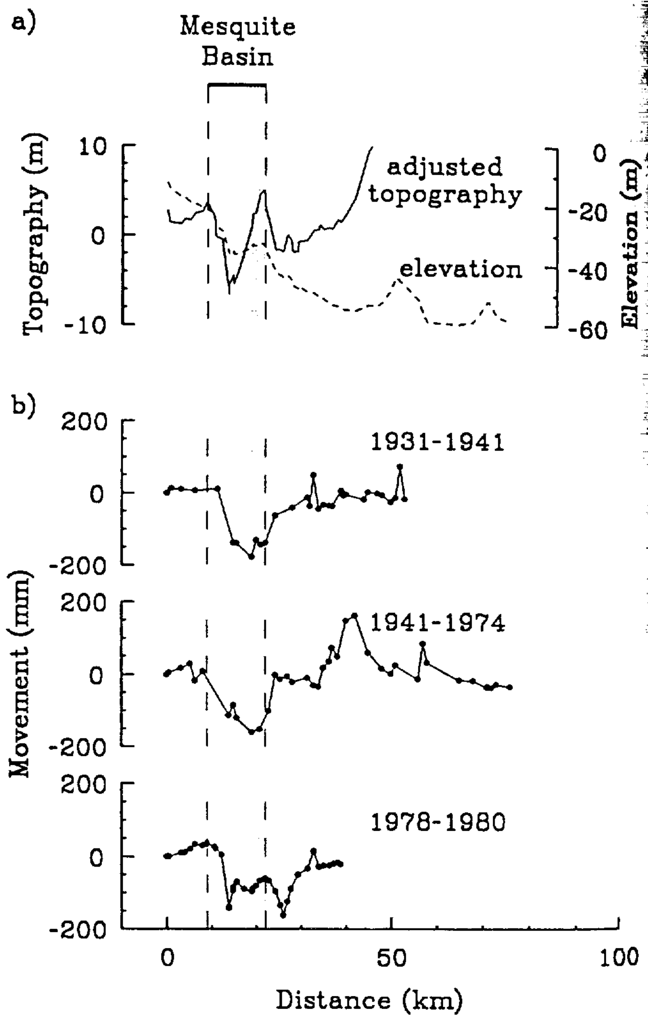

Fig. 5. (a) Elevation (dashed line) along the releveling route between El Centro and the Salton Sea. The adjusted topography (solid line) is the elevation with the northward tilt of −0.0011 radians removed. The 10 m depression between 9 and 22 km is the surfacial expression of the Mesquite Basin. (b) Elevation changes along the leveling route from 1931 to 1941, 1941 to 1974, and 1978 to 1980. Note the strong correlation between deformation and the surface expression of the Mesquite Basin.

The random error for these measurements is comparatively small, less than 1 cm. In addition, elevation-correlated errors (i.e., rod calibration and atmospheric refraction) which can obscure or be mistaken for real tectonic deformation, will not seriously affect the data because of negligible topographic variation along the leveling route (Figure 5a).

The 1931–1941 and 1941–1974 profiles have been modeled as coseismic and postseismic deformation from the 1940 Imperial Valley earthquake [*Reilinger*, 1984]. Displacements for the most recent interval (1978 to 1980) have been modeled as surface deformation from the 1979 earthquake [*Reilinger and Larsen*, 1986]. The most striking feature of the leveling data is the similar pattern of subsidence across the Mesquite Basin observed on all three profiles, suggesting this deformation style is characteristic for the region. Coseismic subsidence for the 1940 and 1979 events are on the order of 10–15 cm, with an additional 15 cm following the 1940 earthquake. Total subsidence for the period 1931 to 1980 is about 40 cm.

Elevation along the leveling route is shown in Figure 5a (dashed line). A relatively constant northward slope of -0.0011 radians is observed. This long-wavelength trend may mask small scale variations, so we construct a modified topographic profile by removing this regional slope (we add 0.0011 radians to the true profile). The modified profile, or adjusted topography, is shown as the solid line in Figure 5a. The 10-meter depression between 9 and 22 km marks the boundary and surface relief along the northern part of the Mesquite Basin. The topographic relief is well correlated with the seismically generated subsidence, strongly suggesting the Mesquite Basin formed by many episodes of seismic activity similar to the 1940 and 1979 events.

Vertical surface slip along the northern section of the 1979 rupture plane ranged from 0 to 30 cm (including 6 months afterslip), while vertical offset along the Brawley fault was 0 to 24 cm [*Sharp et al.*, 1982]. Measurements of vertical slip following the 1940 earthquake were sparse, although the sense of displacement was generally the same as in 1979 [*Sharp*, 1982]. During an earthquake swarm in 1975, up to 20 cm of vertical displacement was observed along the Brawley fault and an additional 20 cm possibly occurred between 1960 and 1975 [*Sharp*, 1976]. In each case, slip was down to the east along the Imperial fault and down to the west along the Brawley fault. Displacement on the Rico fault during the 1979 event was down to the west.

Perhaps the most puzzling and intriguing aspect of deformation in the Mesquite Basin is shown by the offset pattern recorded in the crystalline basement along the Imperial fault. Seismic refraction experiments were conducted by the U.S. Geological Survey in the Imperial Valley during 1979 [*Fuis et al.*, 1984]. Three refraction lines RL-1, RL-2, and RL-3 cross the Imperial fault where shown in Figure 4. (These correspond to *Fuis et al.* [1984] lines 6NW–1SE–1NW, 1ESE, 1E–2W.) The seismic measurements indicate a 1000 m basement offset across the Imperial fault at RL-1, a 500 m offset at RL-2, whereas no basement offset is observed at RL-3. That is, the offset increases to the southeast. Where detectable, the subsurface morphology is down to the east. The basement is defined as rock with $V_p = 5.6$ km/sec, which approximately corresponds to 5 km depth. What makes the basement structure so unusual is its opposite arrangement to the deformation displayed at the surface, where vertical fault offsets measured for the 1940 and 1979 earthquakes generally increased to the northwest. In fact, where the basement structure is maximum (at RL-1), the coseismic vertical surface displacements were either small or non-existent. Presumably, this apparent discrepancy between surface and sub-surface structure must illustrate an important tectonic feature.

AGE OF FAULTING

The correlation between geodetically measured subsidence and the topographic expression shown in Figure 5 strongly suggests this region developed from episodes of seismic activity similar to the 1940 and 1979 earthquakes. In fact, this example clearly illustrates that earthquakes are a fundamental building block of tectonic structures. The 10 m surface depression, together with the subsidence rate and basement morphology, places constraints on the age of the Mesquite Basin, and correspondingly the northern segment of the Imperial fault.

About 5 m of seismic and postseismic slip along the Imperial fault north of the border is required to form the 40 cm subsidence between the earliest and most recent levelings across the Mesquite Basin (1931–1980) [*Reilinger*, 1984; *Reilinger and Larsen*, 1986]. At a slip rate of 40 mm/yr across the Imperial fault, 5 m of potential slip will accumulate in 125 years. The equivalent basin subsidence rate is thus about 3 mm/yr. While depending heavily on the rate of strain accumulation, this analysis is invariant to the earthquake recurrence interval.

At a tectonic subsidence rate of 3 mm/yr, the 10 m depression which outlines the Mesquite Basin would form in 3000 years. This suggests that the tectonic framework underlying the basin, namely the northern Imperial and Brawley faults, is extremely young compared to the 4 to 12 million year age of the Imperial Valley. However, this estimate does not include sediment influx into the Mesquite Basin. While the measured seismic subsidence is about an order of magnitude larger than typical fill rates in arid regions [*Ollier*, 1981], the basin is located in one of the largest river deltas in the United States; presumably sediment influx is high. In fact, the average rate of deposit in the central Imperial Valley is about 1 mm/yr (5 km over the last 5 million years), only slightly smaller than the rate of tectonic subsidence. Overlying sediments may mask a deeper basin, so 3000 years is an extreme minimum duration for basin development.

The lack of an observed basement offset at RL-3 places further constraint on fault age. The geometry and dextral motion of the San Andreas and Imperial faults require extension in the Brawley Seismic Zone. Dip-slip motion along the northern Imperial and Brawley faults helps to fill this requirement. Although geodetic, geologic, and strong-motion data indicate significant vertical displacements along the northern segment of the Imperial fault (north of its intersection with the Brawley fault), apparently insufficient time has elapsed to allow the formation of a detectable basement offset at its northern extent. The lack of offset suggests this region formed relatively recently and is at its earliest stage of tectonic development. *Fuis et al.* [1984] suggest that on intersecting refraction lines in the Imperial Valley, structural boundaries to about 5 km depth agree to within a few tenths of a kilometer. Assuming the refraction data can resolve offsets of 300 m (about 1/2 of the offset measured at RL-2), at a tectonic subsidence rate of 3 mm/yr the maximum age for the northern Imperial fault is about 100,000 years; again very young compared to the 4–12 million year age of the Imperial Valley.

Other evidence support a young age for this segment of the Imperial fault. Models of heat transfer mechanisms suggest the Salton Sea geothermal field (Figure 4) formed within the last 3000 to 20,000 years [*Kasameyer et al.*, 1980, 1984], consistent with the 3000 to 100,000 year age range calculated for the Mesquite Basin. If representative of central Imperial Valley tectonics, this geothermal field likely formed contemporaneously with the Brawley Seismic Zone and the northern Imperial fault. To achieve a balance between thermal constraints and the current composition of the crust, *Lachenbruch et al.* [1985] calculate that heat flow measurements within the Imperial Valley indicate an average extension rate of $\sim 10^{-14}\ s^{-1}$ since the formation of the Salton Trough. At this rate, the differential velocity between the Pacific and North American plates requires that extension and faulting must have been distributed over a relatively wide region (~ 150 km) during the last several million years. Presumably, tectonic and seismic activity, which is presently highly concentrated along the Imperial fault and within the Brawley Seismic Zone, is part of an evolutionary process in which tectonic activity is shifted from one region of the valley to another. The northern Imperial and Brawley faults, Mesquite Basin, and Brawley Seismic Zone may represent the most recent epoch of activity in a rapidly changing fault geometry.

PROPAGATING RIFT?

As discussed above, the relationship between seismicity, dip-slip faulting, and basement offset indicates a young age for the northern segment of the Imperial fault. Similarly, the large basement offset along the central section of the fault (at RL-1) suggests significant vertical slip along this segment in the past. We suggest here a scenario for the recent history of the Imperial fault and the Brawley Seismic Zone, that includes the northwestward propagation of the Gulf of California oceanic rift system.

Although rupture along the Imperial fault is predominately strike slip, the large component of normal motion along the northern segment of the fault is presumably in response to the en echelon geometry of the San Andreas and Imperial faults. These faults may act as transforms associated with a spreading center beneath the Brawley Seismic Zone [*Elders et al.*, 1972; *Johnson*, 1979]. If the northern extent of the Imperial fault, as well as the Brawley Seismic Zone were previously further south (perhaps southeast of El Centro), dip-slip motion would be expected along this segment of the fault. Eventually, a detectable offset would develop in the crystalline basement. As the spreading center (Brawley Seismic Zone) migrated northwest to its present position, so would the vertical movements during seismic events. Although rupture along the fault becomes increasingly strike slip with age, the vertical offset equals the integrated offset through time, and therefore increases with age. This model accounts for the apparent disparity between long-term vertical offsets on the Imperial fault (increasing basement offset to the southeast) and present-day seismic fault slip (maximum dip-slip along the northern segment of the fault).

The rupture pattern for the 1979 earthquake supports this hypothesis (Figure 4). Clearly the northern Imperial and Brawley faults are active components in the stress/strain transfer mechanism between the Imperial and San Andreas faults. Both structures show significant seismic displacements at the surface and at depth. Although displacement along the Rico fault was 10–20 cm vertical with no horizontal offset [*Sharp et al.*, 1982; *Reilinger and Larsen*, 1986], the 1 km rupture length suggests it is only a minor constituent in the regional tectonics. The Rico, Brawley, and the north extension of the Imperial fault, each follow a north-south trend and are uniformly spaced at distances of 6 to 7 km. This geometrical similarity suggests a similar tectonic origin. In fact, the Rico fault may be an older structure reactivated during the 1979 earthquake, although little is known about its past history [*Sharp et al.*, 1982].

A schematic illustration of the temporal evolution of this region is shown in Figure 6. If the Brawley Seismic Zone was further southeast than at present, the Rico fault may have acted as the Brawley fault does today. Similarly, the Brawley fault would have been the northern splay of the Imperial fault, identical to the present north extension. A prehistoric basin would have developed between the Rico and Brawley faults (forming the observed fault offset), similar to the Mesquite Basin. Presumably, as the Imperial fault lengthened to the northwest, the Rico-Brawley fault system no longer influenced the stress/strain distribution between the northern Imperial and southern San Andreas faults. As a result, a new fault developed (north extension) and the

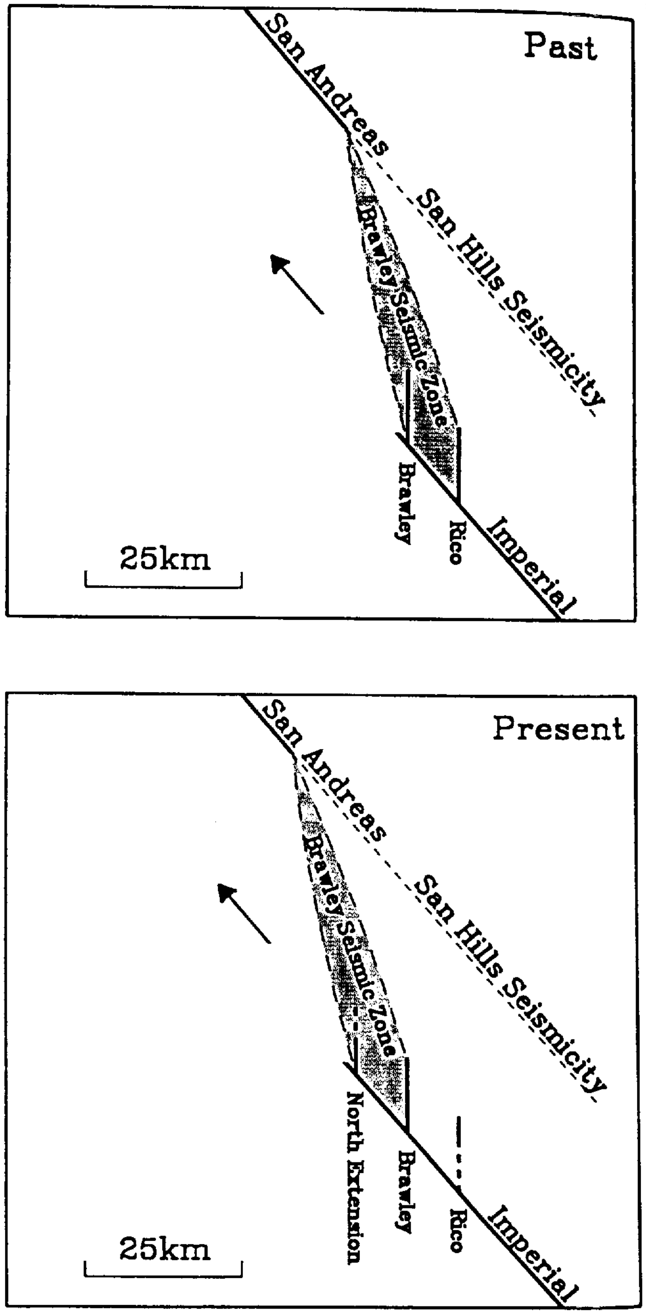

Fig. 6. Schematic diagram of past and present fault configurations in the Imperial Valley illustrating the hypothesized northwesterly migration of the Brawley Seismic Zone. In this model the Sand Hills Seismicity Lineament is the extension of the San Andreas, left dormant after the passage of the Brawley Seismic Zone.

Rico fault died out. Continued migration of the Brawley Seismic Zone may in the future create a new north-south trending structure northwest of the present terminus of the Imperial fault. As the Brawley Seismic Zone shifted to the northwest, so did the southern terminus of the San Andreas fault (Figure 6). The Sand Hills lineament appears to be the remnant of an older segment of the San Andreas, and except for residual seismic activity, left dormant with the northwest passage of the Brawley Seismic Zone.

An apparent inconsistency with this model is that the slip direction on the north extension is down to the east, while slip along the Brawley and Rico faults is down to the west. A distinction is made here between the northern Imperial fault and the north extension. It is the normal movement on the Imperial fault which generates the offset observed in the crystalline basement; the north-trending faults are subsidiary features. Once the Brawley Seismic Zone migrates past its present position, the north extension could maintain its current slip orientation without affecting the tectonic model suggested in Figure 6. It is also conceivable that the slip orientation on this fault could be reversed in the near future (down to the west), or that another fault could develop in its place.

It is possible to make a rough estimate for the migration rate of the Imperial fault and southern Brawley Seismic Zone. Assuming a dip-slip offset rate of 3 mm/yr (estimated above), approximately 330,000 years are required to create the 1000 m basement offset measured along the Imperial fault at RL-1. The 3000 to 100,000 year age for the fault segment 20 km to the northwest (at RL-3) indicates that the Brawley Seismic Zone has migrated about 20 km during the last 250,000 to 300,000 years. This yields a migration rate of about 7 cm/yr. While this rate is only a very crude estimate, it is significant to note that it is comparable to typical plate motion velocities (i.e., several centimeters per year). In fact, the estimated spreading rate in the mouth of the Gulf of California averaged over the last 3 million years is 4.9 cm/yr [e.g., *DeMets et al.*, 1987].

If the Brawley Seismic Zone represents the crustal manifestation of a subcrustal spreading center, we speculate that its northwesterly migration is directly associated with the propagation of the Gulf of California rift system into the North American continent. This hypothesis assumes that the localized transient phenomenon observed along the northern Imperial fault is characteristic of more regional tectonic processes throughout the Salton Trough. Clearly, the Imperial Valley and Brawley Seismic Zone are undergoing rapidly changing tectonics. Understanding the kinematics of these changes will help constrain the dynamic processes which control the transition between crustal spreading in the Gulf of California and transform motion along the San Andreas fault.

CONCLUSIONS

Geodetic, seismic, tectonic, and heat flow data in the Imperial Valley suggest that the northern segment of the Imperial-Brawley fault system is extremely young compared to the 4 to 12 million year age of the Imperial Valley. We find a minimum age of 3000 years based upon the relationship between topography and earthquake induced geodetic displacements, and estimate a maximum age of 100,000 years based upon observed basement offsets across the Imperial fault determined from seismic refraction surveys. A young age is consistent with heat flow data, which indicate a distributed and ephemeral pattern of faulting in the Imperial Valley [*Lachenbruch et al.*, 1985].

In addition, we speculate that the apparent incompatibility along the Imperial fault between the observed seismic vertical displacements (maximum to the north) and the offset recorded in the crystalline basement (maximum to the south) is a direct result of the northwestward propagation of the Imperial fault and Brawley Seismic Zone. A series of evenly spaced north-trending surface ruptures and the Sand Hills seismicity lineament are consistent with this hypothesis. A 7 cm/yr migration rate is calculated from measured surface displacements and from variations in basement morphology along the Imperial fault. The migration of the Brawley Seismic Zone and Imperial fault may be associated with the propagation of the Gulf of California rift system into the North American continent.

Acknowledgments. We thank the National Geodetic Survey and in particular Emery Balazs for providing the leveling data reported here. Reviews by Kerry Sieh, Hiroo Kanamori, William Prescott, Eugene Humphreys, and Carl Johnson were very helpful and substantially improved the present manuscript, as were comments by Gary Fuis on a much earlier version. We thank Liz Henderson for formatting the text for *JGR*. This work was supported in part by NASA grant NAG 5-814 and by U.S. Geological Survey contracts 14-08-0001-61679 (MIT) and 14-08-0001-61354 (Caltech). Caltech Division of Geological and Planetary Sciences contribution 4871.

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(Received May 3, 1990;
revised February 26, 1991;
accepted November 5, 1990.)