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This is a Semi-Annual Status Report on research conducted between 22 March 1990 and 21 September 1990 under NASA Grant NAG 5-814, entitled "The Interpretation of Crustal Dynamics Data in Terms of Plate Motions and Regional Deformation near Plate Boundaries." This grant supports the research of one Investigator (S. C. Solomon), two Research Staff (E. A. Bergman and R. Reilinger), and two Ph. D. students (A. F. Sheehan and C. J. Wolfe) on behalf of the NASA Geodynamics and Crustal Dynamics Programs.

The focus of the research has been in two broad areas during the most recent 6-month period: (1) the nature and dynamics of time-dependent deformation and stress along major seismic zones, and (2) the nature of long-wavelength oceanic geoid anomalies in terms of lateral variations in upper mantle temperature and composition. The principal findings of our research to date are described in the accompanying appendices. The first is a preprint of a recently completed paper, the second and third are abstracts of papers presented at the 1990 Fall AGU Meeting, and the fourth is a report of a recent GPS measurement campaign in southern California.

APPENDIX 1

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

by Shawn Larson and Robert Reilinger

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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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Abstract

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 4 to 5 million year 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 80,000 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, which also suggest that the current patterns of seismicity and faults in the Imperial Valley are not long lived. The current fault geometry and basement morphology suggest northwestward growth of the Imperial fault and migration of the Brawley Seismic Zone. We suggest 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 is a 150 by 300 km structural depression, 4 to 5 million years old, and 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 they are greenschist-facies, metasedimentary rocks [Fuis *et al.*, 1984].

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 left-lateral 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 has ruptured historically, in 1940 ($M_S = 7.1$) and in 1979 ($M_L = 6.6$); episodes of creep have been recognized along the fault since 1966 [Allen *et al.*, 1972]. Other major events 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 northwestward 33.1 km from a point 5 km north of the border 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-south. We refer to this segment as the north extension. Parallel and 6 km east of the north extension, the Brawley fault ruptured in 1979 along a 13 km surface break. The rupture pattern generally featured left-stepping en echelon cracks that extended a few millimeters to a few centimeters [Sharp el al., 1982]. A third, yet relatively minor 1 km north-south 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, 1972; 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 higher displacement (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 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 in 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 structure dipping 70° to the southwest (Figure 3, dashed lines). Neither fault broke the surface but roughly 1 m slip at depth was 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 procedures 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 (Figure 3), here referred to as the Sand Hills seismicity lineament. 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].

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 magnitude for the 1940 event ($M_S = 7.1$ vs. $M_S = 6.6$). North of the border, however, the magnitude of horizontal surface displacement was relatively constant for the two earthquakes. One explanation 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 releaved aseismically.

If the entire 49 mm/yr movement between the Pacific and North American plates predicted by new global plate models (NWVAL 1) [DeMets *et al.*, 1987] is accommodated across the Imperial fault, 1.0 meter 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]. Triangulation and trilateration measurements from 1941 to 1981 in the central Imperial Valley indicate an average displacement across the Imperial fault of 40 mm/yr [Snay and Drew, 1988]. Preliminary results utilizing the Global Positioning System (GPS) suggest a similar rate between 1986 and 1988, although interpretation of these measurements have been complicated by large displacements from the 1987 Superstition Hills earthquake sequence [Larsen *et al.*, 1988].

Assuming 40 mm/yr of plate motion across the Imperial fault, 1.0 m of potential slip will accumulate in 25 years. This will be 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 likely-hood of aseismic deformation, as well as the seismic and geodetic models indicating asperities along the 1979 rupture plane, it is reasonable to expect that the average slip generated along the northern Imperial fault during each earthquake (or 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.

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. That is, the Mesquite Basin underwent subsidence during each event.

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 earlest and most recent levelings across the Mesquite Basin (1931-1980) [Reilinger, 1984; Reilinger and Larsen, 1986] (additional slip is required to the northest of the basin and along the Brawley fault to produce the detailed deformation pattern). At a plate motion 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 5 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, 1978], 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 time 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. Assuming the refraction data can resolve offsets of 250 m (1/2 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 80,000 years; again very young compared to the 4-5 million year age of the Imperial Valley.

Other evidence support a young age for this segment of the Imperial fault. Models of the heat transfer mechanisms, suggest the Salton Sea geothermal field (Figure 4) formed within the last 3500 to 12,000 years [Kasameyer *et al.*, 1980], consistent with the 3000 to 80,000 year age range calculated for the Mesquite Basin. If representative of central Imperial Valley tectonics, the geothermal field likely formed contemporaneously with the Brawley Seismic Zone, and correspondingly with the northern Imperial fault. To achieve a balance between thermal constraints and the current composition of the crust, 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 [Lachenbruch *et al.*, 1985]. 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 4-5 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

The relationship between seismicity, dip-slip faulting, and basement offset indicate a young age for the northern segment of the Imperial fault. Similarly, the larger basement offset along the central section of the fault (at RL-1) suggests significant vertical slip along this segment in the past.

We suggest a scenario for the recent history of the Imperial fault and Brawley Seismic Zone, which is consistent with the notion of 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 older section of the fault would change to strike slip, a vertical offset would be recorded in the basement. This model can account 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 approximately 10 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. In fact, the Rico fault may be an older structure reactivated during the 1979 earthquake. 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 strong geometrical relationship among the three faults suggest a similar tectonic origin. 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 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 may 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.

It is possible to make a rough estimate for the migration rate of the Imperial fault and Brawley Seismic Zone. Assuming a dip-slip offset rate of 3 mm/yr (estimated above), approximately 330,000 years are required to form the 1000 m basement offset measured along the Imperial fault at RL-1. The 3000 to 80,000 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 over 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 quite comparable to the 4.8 cm/yr spreading rate in the Gulf of California averaged over the last 3 million years [DeMets *et al.*, 1987]. In fact, the northwesterly migration of the

Brawley Seismic Zone, and its underlying spreading center, may be directly associated with propagation of the Gulf of California rift system into the North American continent.

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 5 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 a maximum age of 80,000 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 a disparity 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-south surface ruptures and the Sand Hills seismicity lineament are consistent with this hypothesis. A 7 cm/yr migration rate, similar to the rate of oceanic spreading in the Gulf of California, 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.

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Figure Captions

Figure 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].

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

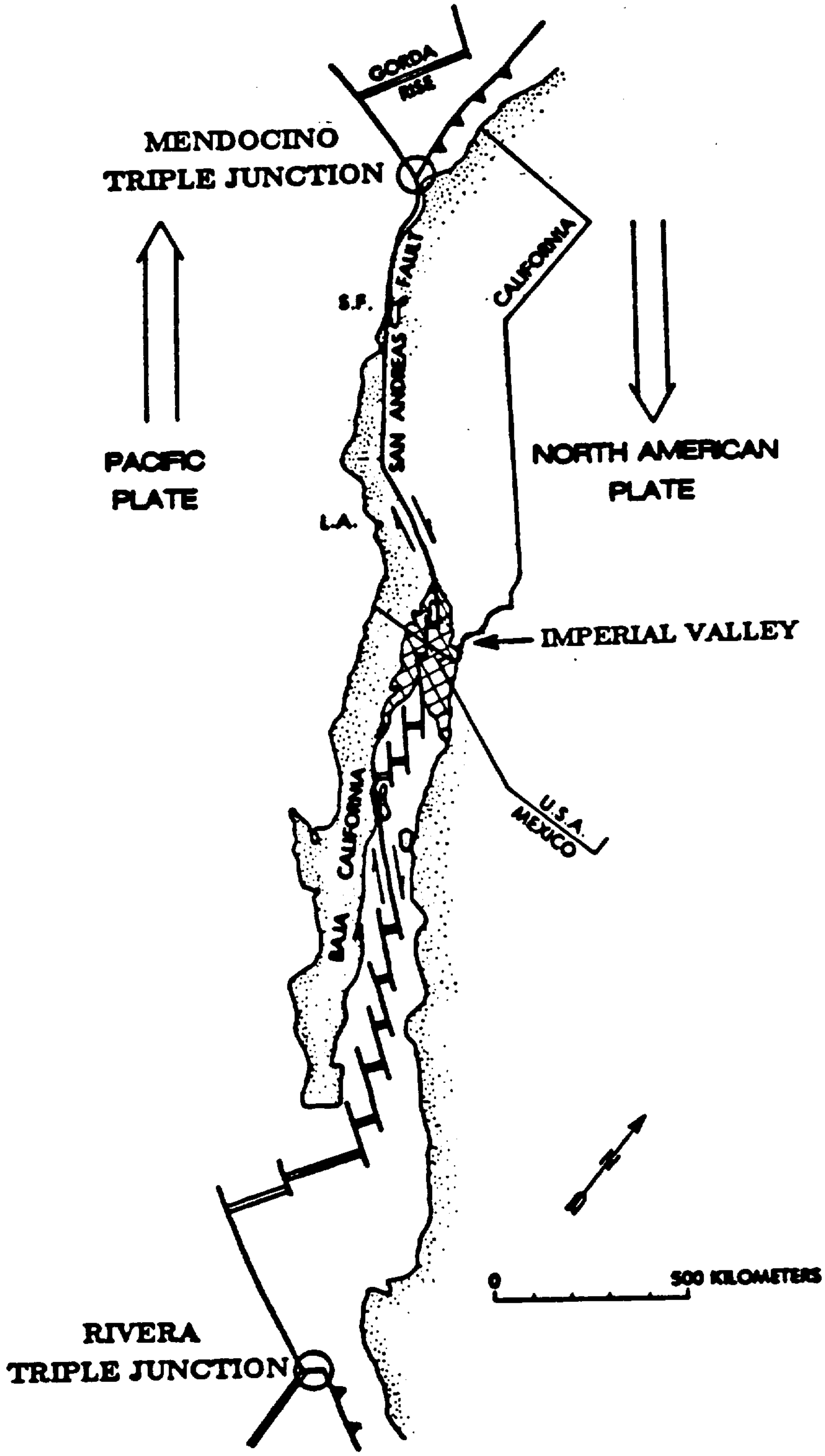
Figure 3 - Seismicity in the Imperial Valley between 1932 and 1989 (Caltech/USGS Catalog). Major events include the 1940 Imperial Valley (M_S = 7.1), 1968 Borrego Mountain (M_L = 6.5), 1979 Imperial Valley (M_S = 6.6), and the 1987 Superstition Hills (M_S = 6.6, M_S = 6.2) earthquakes. The Brawley Seismic 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 in 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

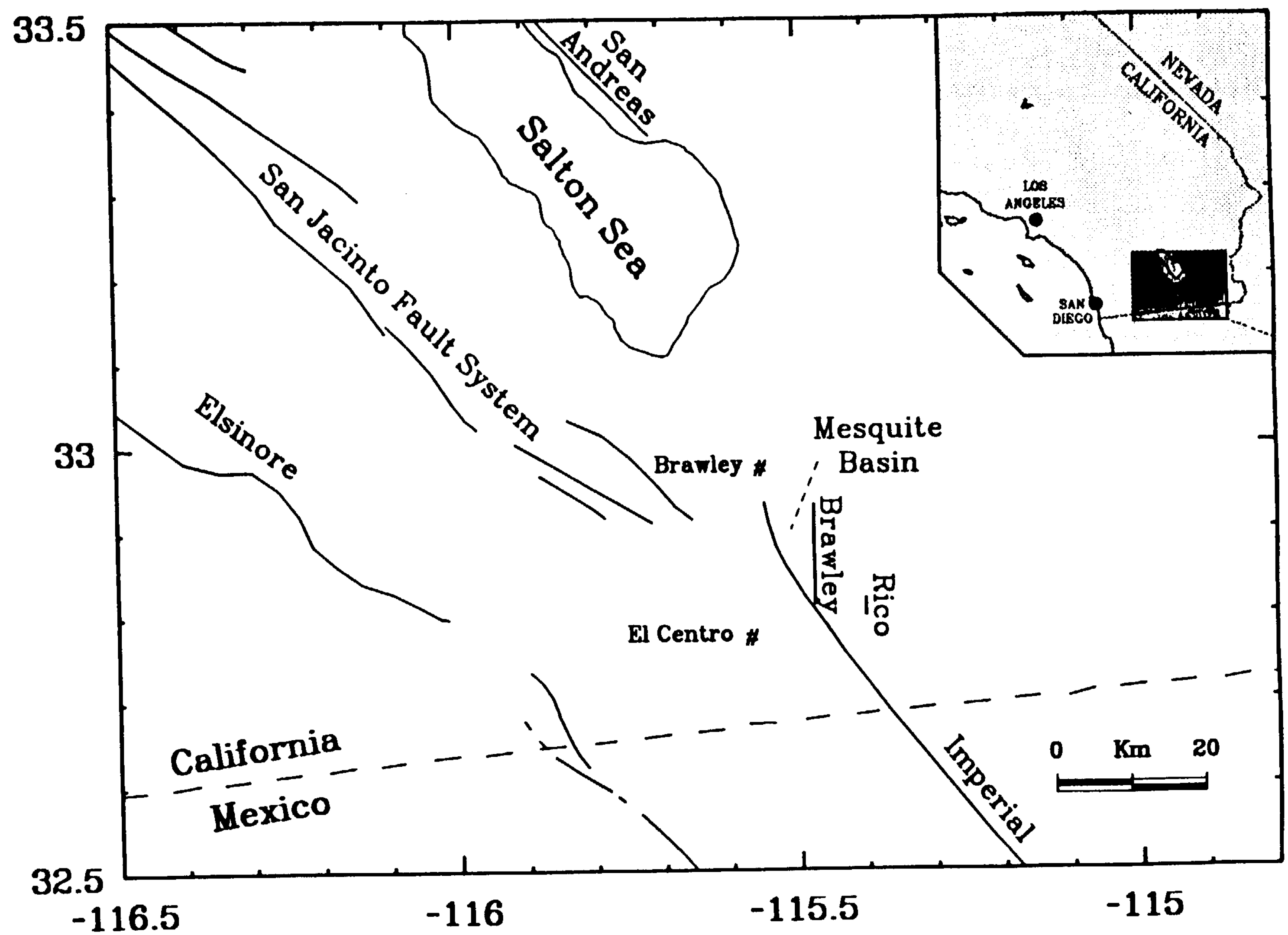
motion.

Figure 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 Geothermal Field is the shaded pattern along the southern section of the Salton Sea. 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).

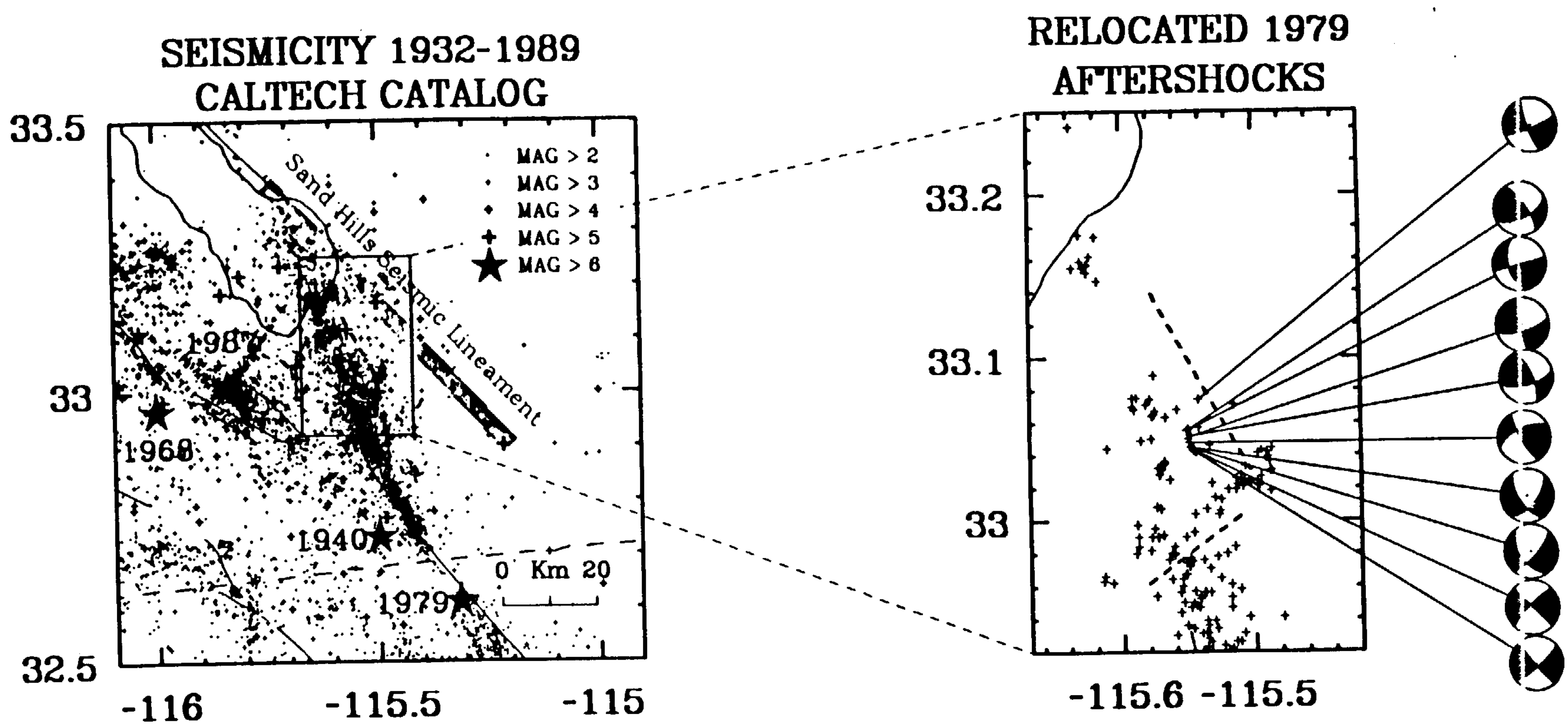
Figure 5 - Shown in a) is the elevation (dashed line) along the releveling route between El Centro and the Salton Sea. The adjusted topography (solid line) is the elevation with the northward tilt of -0.0011 radians removed. The 10 meter depression between 9 and 22 km is the surfacial expression of the Mesquite Basin. Shown in b) are the 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.

Figure 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.

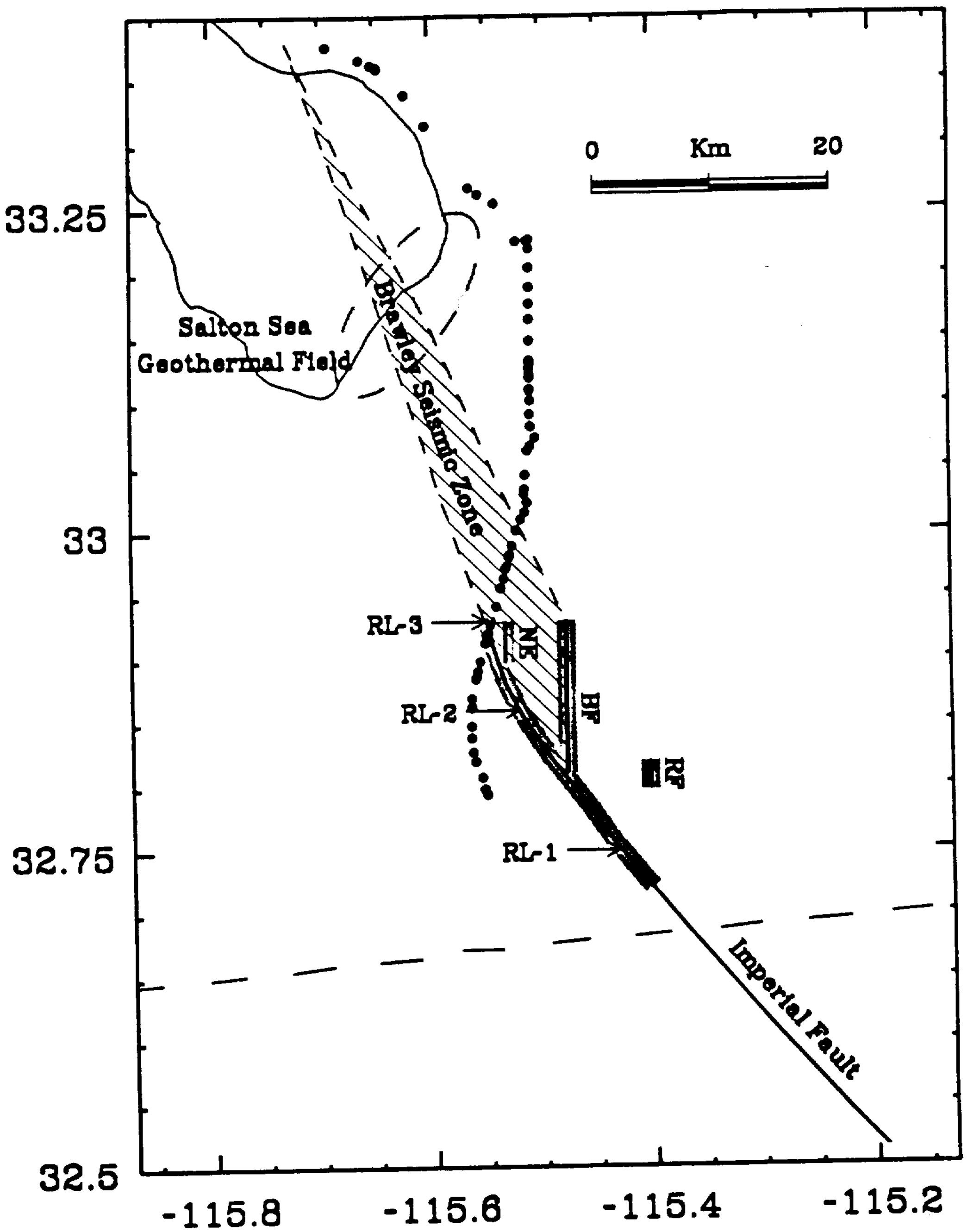

GORDA
RISE
MENDOCINO
TRIPLE JUNCTION
CALIFORNIA
S.F.
SAN ANDREAS FAULT
PACIFIC
PLATE
NORTH AMERICAN
PLATE
L.A.
IMPERIAL VALLEY
U.S.A.
MEXICO
BAJA CALIFORNIA
0
500 KILOMETERS
RIVERA
TRIPLE JUNCTION



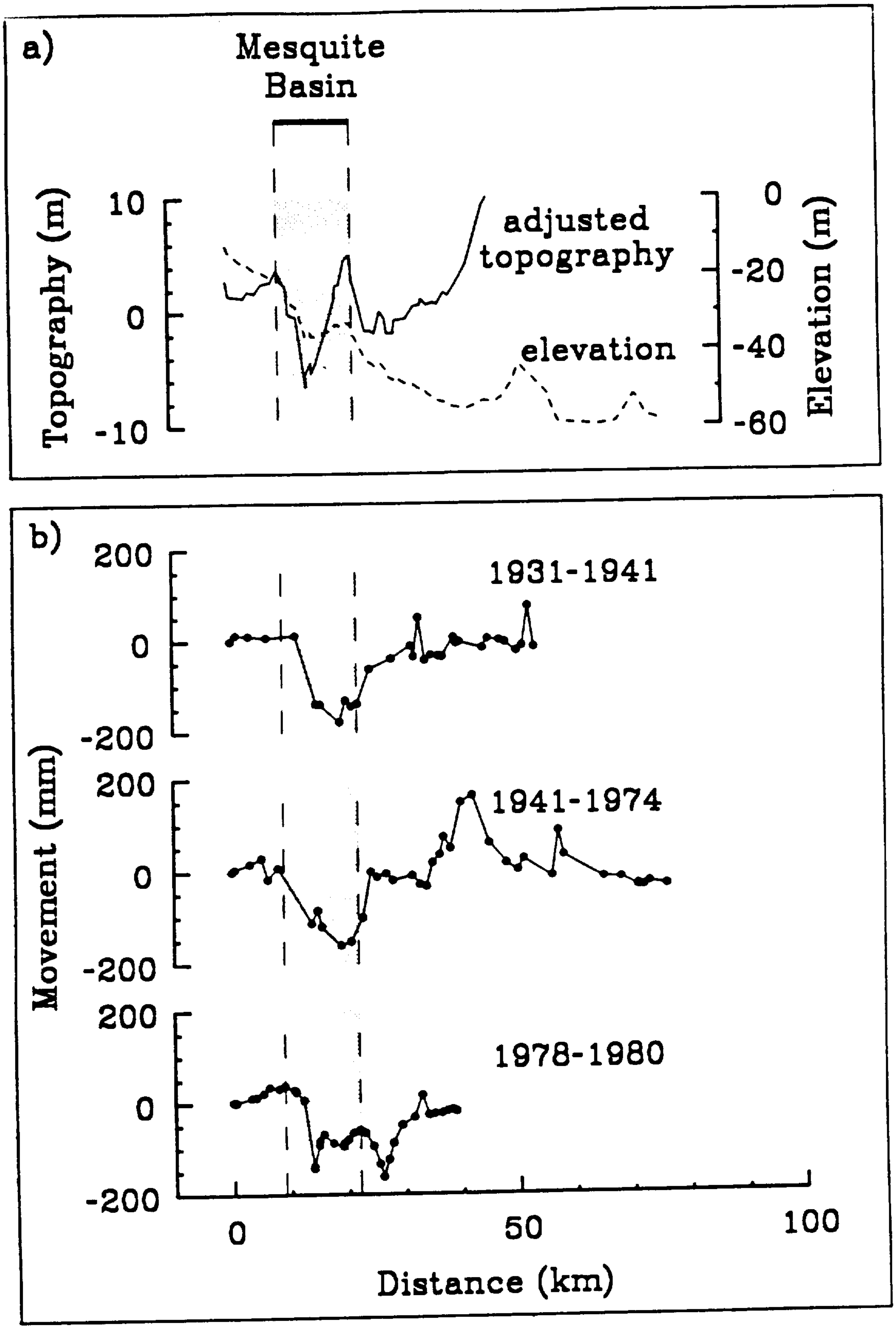
San Andreas
Salton Sea
San Jacinto Fault System
Elsinore
Brawley #
El Centro #
Mesquite Basin
Brawley
Rico
Imperial
California
Mexico
0 Km 20
NEVADA
CALIFORNIA
LOS ANGELES
SAN DIEGO
33.5
33
32.5
-116.5
-116
-115.5
-115

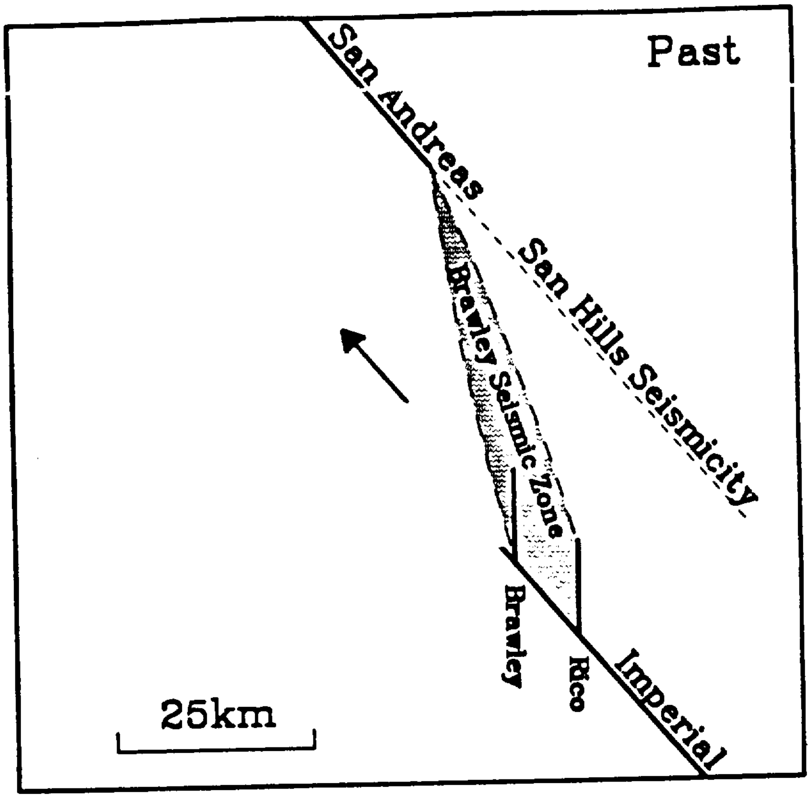

SEISMICITY 1932-1989
CALTECH CATALOG
33.5
33
32.5
-116
-115.5
-115
MAG > 2
MAG > 3
MAG > 4
MAG > 5
MAG > 6
Sand Hills Seismic Lineament
1987
1968
1940
1979
0 Km 20
RELOCATED 1979
AFTERSHOCKS
33.2
33.1
33
-115.6 -115.5

3

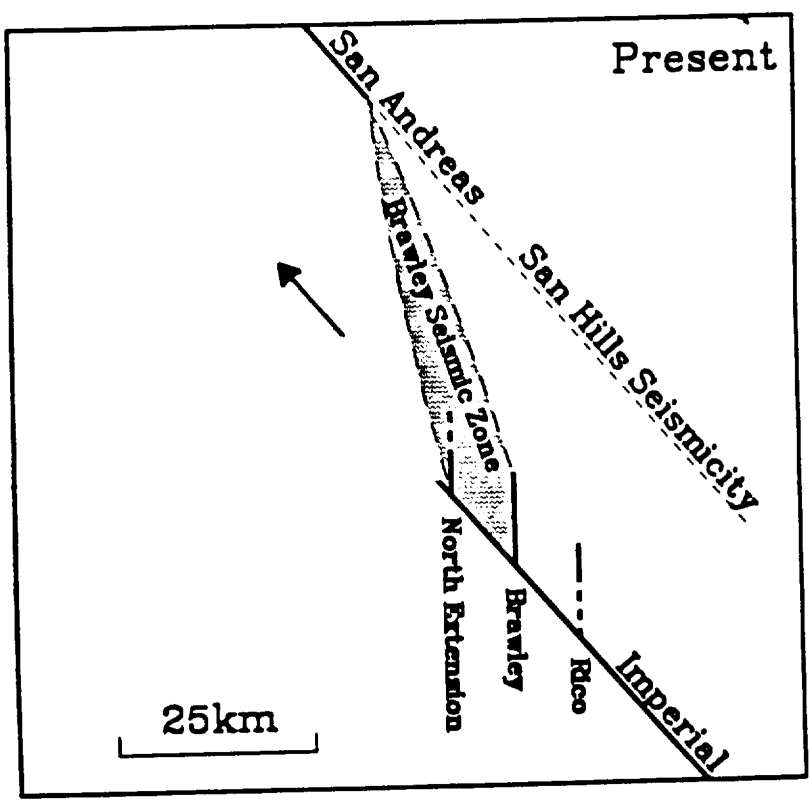


33.25
33
32.75
32.5
-115.8
-115.6
-115.4
-115.2
0
Km
20
Salton Sea
Geothermal Field
Brawley Seismic Zone
RL-3
RL-2
RL-1
NE
BF
RF
Imperial Fault


a)
Mesquite
Basin
10
0
-10
Topography (m)
adjusted
topography
elevation
0
-20
-40
-60
Elevation (m)
b)
200
0
-200
1931-1941
200
0
-200
1941-1974
200
0
-200
1978-1980
Movement (mm)
0
50
100
Distance (km)



Past
San Andreas
San Hills Seismicity
Brawley Seismic Zone
Brawley
Rico
Imperial
25km



Present
San Andreas
San Hills Seismicity
Brawley Seismic Zone
North Extension
Brawley
Rico
Imperial
25km

APPENDIX 2

Rift Grabens, Seismicity, and Volcanic Segmentation of the Mid-Atlantic Ridge: Kane to Atlantis Fracture Zones

by Jian Lin and Eric A. Bergman

From *Eos Trans. AGU*, 71, 1572, 1990

This paper presents results from an analysis of bathymetric, earthquake, and gravity data along an 800-km length of the Mid-Atlantic Ridge (MAR) which demonstrates an inherent relationship among the formation of rift grabens, seismicity, and volcanism along the MAR. The morphology of the rift valley was examined using Sea Beam data collected along the entire ridge length. Rift-bounding fault zones were identified on the bathymetric maps and were cataloged by their geometric parameters and spatial distribution along the ridge axis. We also investigated moderate earthquakes (m_b>4.0) that occurred during 1964-1986 along this portion of the MAR. More than 150 events were relocated from the catalog of the International Seismological Centre (ISC) using the hypocentroidal decomposition technique of Jordan and Sverdrup (1981). Bias in the epicenters was reduced significantly by requiring Kane transform earthquakes to be located on the known trace of the transform, and by matching solutions of three 1985 events with that determined from a local OBS-OBH network. This portion of the MAR contains 15 volcanic segments, each 20-80 km long, separated by transform and non-transform discontinuities (Sempere et al., 1990). 'Bulls eye'-shaped gravity lows were found over the shallowest points of several segments, indicating enhanced magmatic accretion at the center of the segments (Lin et al., 1990).

The rift structure is characterized by the frequent occurrence of *half-graben* structures with lengths up to 50 km and relief up to 2 km. By analogy with examples from continental rifts, half-grabens represent areas of prolonged extension and are the primary cause of asymmetric rift features. More than 40 half-grabens with relief greater than 1 km were identified in the survey area; most of them strike parallel to the ridge axis and cluster near the distal ends of volcanic segments. Most of the relocated earthquakes occurred within 20 km of the ridge axis. The majority of them (approximately 85%), including many events which occurred as part of earthquake swarms, are found to be inside the half-grabens or in close vicinity. We suggest that the concentration of half-grabens and seismicity reflects infrequent magmatic supply and prolonged brittle failure of the lithosphere near distal ends of the MAR volcanic segments. In contrast, frequent dike injections along the shallowest portions of the segments might inhibit the formation of major half-grabens through frequent release of tectonic stresses and/or rapid infilling of fault-generated topography.

APPENDIX 3

Differential Shear Wave Attenuation in the North Atlantic Region

by Anne F. S. Sheehan and Sean C. Solomon

From *Eos Trans. AGU*, **71**, 1448-1449, 1990

We have measured SS-S differential attenuation as a means to search for long-wavelength lateral variations in upper mantle thermal structure in the vicinity of the Mid-Atlantic Ridge. A spectral ratio technique is employed to obtain measurements of differential t* between horizontally polarized S and SS phases obtained from earthquakes recorded by the long period stations of the global digital seismic network (GDSN). SS-to-S spectral amplitude ratios are formed, and differential attenuation (δt^*) is computed from the slope of the log of the spectral ratios generally within the frequency band 0.02 to 0.10 Hz. The convention we employ is that

$$\delta t^* = t^*_{SS} - t^*_{S} = \int_{SS} \frac{ds}{Q_\beta(s)\, v_\beta(s)} - \int_{S} \frac{ds}{Q_\beta(s)\, v_\beta(s)}$$

where $v_\beta(s)$ is the shear wave velocity and $Q_\beta(s)$ the quality factor along the path. The individual measurements of δt^* show much scatter and indicate an average δt^* of 2.6 ± 1.4 s for the North Atlantic region. Spectral ratios were stacked by lithospheric age groups to obtain more stable estimates of δt^*. Our preliminary results given an average δt^* value for the stacked ratios of 1.8 ± 0.4 s, which corresponds to an average Q_{SS-S} of 154 ± 36, and indicate at most a weak decrease in δt^* with distance from the axis of the Mid-Atlantic Ridge corresponding to increasing lithospheric age. Along-axis estimates of shear wave attenuation provide additional constraints on upper mantle thermal and compositional structure in our ongoing study of shear wave travel time, geoid, and bathymetry anomalies along the axis of the Mid-Atlantic Ridge.

APPENDIX 4

Analysis of Crustal Deformation Along the Southernmost Segment of the San Andreas Fault System, Imperial Valley, California

by R.E. Reilinger

GPS Field Campaign Report

Analysis of Crustal Deformation Along the Southernmost Segment of the San Andreas Fault System, Imperial Valley, California: Implications for Earthquake Prediction

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(617) 253-7860

INVESTIGATIONS

This project involves using geodetic observations in conjunction with other geophysical and geological information to investigate contemporary tectonic processes along the southernmost segment of the San Andreas fault system. Our primary efforts during the present contract period include:

1. Organizing and archiving GPS observations made in February/March 1990, and developing a uniform set of benchmark descriptions for all sites observed during this and previous surveys in the Salton Trough-Riverside County region.

2. Continuing analysis and interpretation of 1986, 1988 and 1989 GPS measurements in the Imperial Valley-Salton Trough with emphasis on regional strain accumulation and strain release associated with the 1987 Superstition Hills earthquakes.

RESULTS

1. From February 18 through March 9, 1990 a high precision GPS network was established along an approximately 400 km segment of the Pacific-North American plate boundary (Figure 1) from the Gulf of California in Northern Mexico to just south of the junction of the San Andreas and San Jacinto faults (~34°N). Participating institutions in the field campaign included: Caltech, CICESE, L-DGO, MIT, NGS, Riverside County, UNAVCO, U. of Mexico, U.T., Dallas, and U. of Nevada. A total of 103 primary stations were observed, most for 2 to 3 days. In addition half sessions (~3–4 hours) were observed at 31 sites near the San Andreas (Banning-Mission Creek segments), San Jacinto and Elsinor faults, and 5 sites were observed in a kinematic survey within a pre-existing EDM network straddling the Imperial fault in Northern Mexico (2 of these kinematic sites were also observed statically). Dense coverage (~5–10 km site spacing) was also established along the southernmost San Andreas and Imperial faults in S. California. Coverage extends to 150 km from the active fault systems.

   All data collected by university and Riverside County participants have been archived with the UNAVCO archiving facility under the direction of Dr. Judah Levine. UNAVCO is currently translating these Trimble data to RINEX format for distribution to participants in the Salton Trough- Riverside County experiment. In addition, descriptions are being generated in NGS format for all benchmarks in the STRC network. These descriptions will be made available to any interested group with the capability to respond in the event of an earthquake within the network.

2. Shawn Larsen has completed initial reduction of the 1988 and 1989 static GPS observations made with TI-4100 receivers using the Bernese 3 software at Caltech (reduction of 1989 Trimble data has been hampered by severe ionospheric disturbances during the campaign). Large station displacements between 1986 and 1988 are attributed to the November 24, 1987 Superstition Hills earthquake sequence. Displacements at 3 sites within 3 km of the surface rupture approach 0.5 m. Eight additional stations within 20 km of the seismic zone are displaced at least 10 cm. This is the first occurrence of a large earthquake (Ms 6.6) within a preexisting GPS network. Best-fitting uniform slip models of rectangular dislocations in an elastic half-space indicate 130 cm right-lateral displacement along the northwest-trending Superstition Hills fault and 30 cm left-lateral displacement along the conjugate northeast-trending Elmore Ranch fault. The geodetic moments are 9.4×10^{25} dyne-cm and 2.3×10^{25} dyne-cm for the Superstition Hills and Elmore Ranch faults respectively. Distributed slip solutions using Singular Value Decomposition suggest near uniform displacement along the Elmore Ranch fault and concentrated slip to the northwest and southwest along the Superstition Hills fault. A significant component of non-seismic secular displacement is observed across the Imperial Valley for the interval 1986-1988 which is attributed to plate-boundary deformation.

   To investigate strain accumulation across the Imperial Valley, station displacements are computed at 29 stations for the period 1986-1988 and 11 stations for the period 1988-1989. The earlier measurements indicate 5.9 ± 1.0 cm/yr right-lateral differential velocity across the Valley, although the data are strongly influenced by the Superstition Hills earthquake sequence. In addition, some measurements, especially those indicating large east-west displacements, are suspect for large errors (most likely in 1986 survey). The 1988-1989 GPS displacements are best modeled by 5.2 ± 0.9 cm/yr of plate boundary deformation, but rates calculated from conventional geodetic measurements (3.4 - 4.3 cm/yr) fit the GPS data nearly as well. There is evidence from GPS and VLBI observations that the present slip rate along the southern San Andreas fault is smaller than the long term geologic estimate, suggesting a lower earthquake potential than is currently assumed. Incorporation of the 1990 observations in this analysis should provide better resolution for strain accumulation across the valley as a whole as well as along individual faults.

PUBLICATIONS

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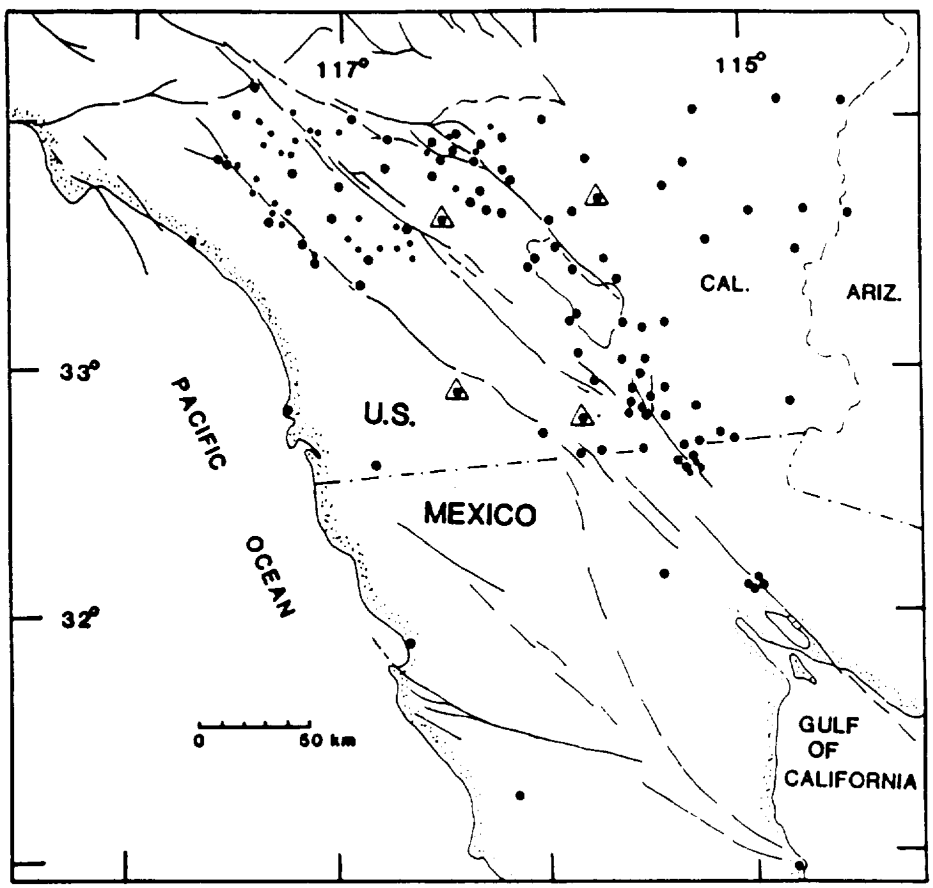

Figure 1. GPS stations observed during the 1990 Salton Trough-Riverside County campaign. Large dots show primary stations, small dots half-session and kinematic sites.