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A MICROEARTHQUAKE STUDY IN THE SALTON SEA GEOTHERMAL AREA, CALIFORNIA

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ABSTRACT

Earthquake activities in the Salton Sea geothermal field were monitored for 8 weeks in 1975 with an array consisting of five portable seismographs and two USGS permanent stations. Two to three events per day ($M_L < 3.0$), commonly occurring in clusters along with intermittent swarm activities, characterize the seismicity of the study area. Focal depths decrease toward the geothermal area where they range from 0.5 to 3.5 km, suggesting aseismic creep occurs at higher temperature regime in the deeper part. The previously inferred Brawley fault is probably offset into two segments but connected by a leaky transform fault where the crustal spreading is reflected by normal faulting in one earthquake swarm and the crustal shearing by strike-slip faulting in another more active swarm. The activities of the latter swarm were poorly correlated with tidal gravity.

INTRODUCTION

A seismicity study in a geothermal area is of importance in understanding the stress release pattern, active faulting or fracturing system, and earthquake risk in geothermal energy extraction. This report deals with a preliminary seismicity study made as part of a multi-disciplinary research effort conducted in the Salton Sea geothermal area, the largest of the known geothermal areas in the Imperial Valley.

The Salton Sea geothermal area lies at the southeastern end of the Salton Sea in the Imperial Valley (Figure 1) which forms a major portion of the Salton Trough physiographic province in the southern California region. The valley is a structural trough filled with lacustrine and deltaic silts, sands, and gravels of late Tertiary age, and by thicker sequences of Quaternary alluvium and lake sediments (Dibblee, 1954). The sediments reach a thickness of 6 km toward the axis of the valley (Biehler, 1964). Quaternary volcanism has left five small rhyolite domes near the center of the present geothermal area (Robinson *et al.*, 1976). The margins of the valley are step-faulted with the bordering mountains consisting of Mesozoic and older granitic and metasedimentary basement rocks. Elders *et al.* (1972) and others have postulated that the Salton Trough was formed by a combination of tensional and right-lateral strike-slip movements associated with the opening of the Gulf of California.

Earthquake swarms are common in the Imperial Valley. The swarm that occurred near Brawley in 1975 is by far the most well studied one in the Imperial Valley (Johnson and Hadley, 1976; Sharp, 1976; Johnson and Hanks, 1976; Hill *et al.*, 1976; Sauck, 1975). Four swarms observed during the first year after the permanent USGS seismographic network was installed in the Valley were reported by Hill *et al.* (1975). It is very likely that additional swarms go undetected. For example, two swarms observed during our study were too weak to be recorded by the more remote USGS stations.

Previous swarm activity near the Obsidian Buttes in the Salton Sea geothermal area was reported by Brune and Allen (1967) and Hill *et al.* (1975). In the East

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Mesa geothermal area, two swarms were reported by Combs and Hadley (1977). Here we present the seismicity observed between July 25 and September 20, 1975 as well as the fault-plane solutions of two swarms, and discuss their tectonic implications concerning the Salton Sea geothermal area.

METHOD

In order to accurately locate hypocenters and detect small events, five high-gain Kinemetrics PS-1 portable seismic packs along with Ranger seismometers were installed around the Salton Sea geothermal field (Figure 2). The instrumentation has been described in detail by Prothero and Brune (1971). A time base was established at the beginning and the end of each 24-hr record with a WWV receiver. A temperature compensated quartz crystal clock provided 20 sec timing marks with an accuracy of ±0.3 ppm over the temperature from 0° to 50°C. Seismograms were recorded on smoked paper at a speed of 1 mm/sec. This allowed P-wave arrivals to be picked with an accuracy of −0.05 to 0.10 sec. *S*-wave arrivals could not be accurately timed and therefore were not used.

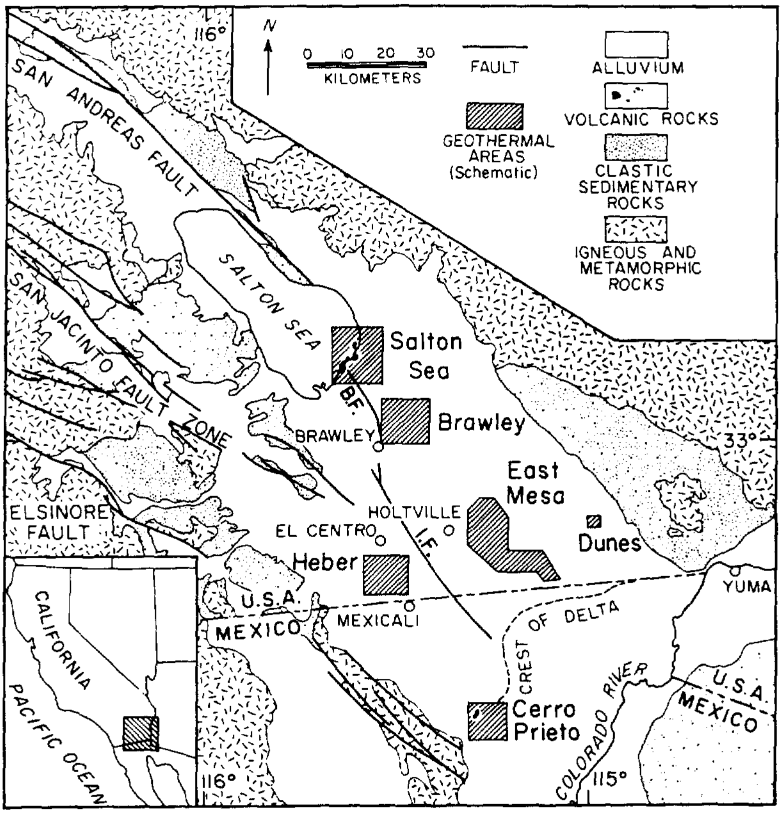

FIG. 1. Generalized geological map of the Imperial Valley and adjacent area and locations of known geothermal areas. B.F., inferred Brawley fault; I.F., Imperial fault (after Robinson et al., 1976).

The velocity structure used in this study was modified from Biehler's (1964) by introducing thin gradational layers (Johnson and Hadley, 1976) in order to minimize destabilizing effects on the first-motion study. Station delay times were determined from a 900 kg calibration shot detonated near the center of the array. Structural differences along the ray paths, excluding the USGS Superstition Mountain Station SUP, were the main factors contributing to the delay times as the station elevations differed by less than **40** m (Table 1). These station delays were used along with the computer program HYPO71 (Lee and Lahr, 1972) to locate the hypocenters. The relocated shot point was within 10 m horizontally and **40** m vertically of the true location. The root-mean-squares of the travel-time residuals for hypocenters in this

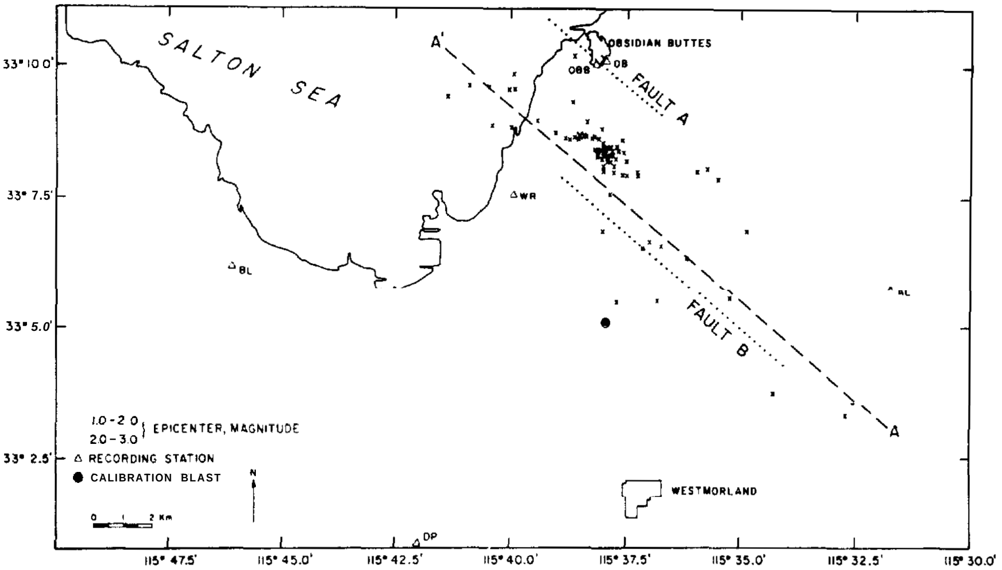

FIG. 2. Epicenter distribution around the Salton Sea geothermal field (July **25, 1975** to September **22, 1975**), including swarm activities. AA' represents surface trace **of** cross section **shown** in Figure **5.** Faults A and B are explained in Figure **9.**

TABLE 1

STATION DESCRIPTIONS

Station	Latitude	Longitude	Elevation (m)	Delay (sec)	Rock Type
AL	33°05.73'N	115°31.73'W	−56	0.05	Alluvium
BL	33°06.22'N	115°46.15'W	−65	−0.15	Alluvium
DP	33°00.96'N	115°42.07'W	−31	−0.23	Alluvium
OB	33°10.11'N	115°37.99'W	−60	−0.42	Volcanic
OBB(USGS)	33°10.04'N	115°38.20'W	−61	−0.41	Volcanic
SUP(USGS)	33°57.31'N	115°49.43'W	221	−0.75	Metasediments
WR	33°07.56'N	115°39.99'W	−70	0.10	Alluvium
Shot point	33°05.27'N	115°37.90'W			

study range from 0.0 to **0.3** sec with **95** per cent less than 0.2 sec. The locations of hypocenters are probably accurate to within 1 km.

The magnitude of an event was estimated with an empirical formula relating total signal duration (D) to the Richter magnitude (M_L), i.e., $M_L = AD + B$. The signal duration was measured from the onset of the P arrival to the point where the trace amplitude fell below 0.5 mm which represents a signal-to-noise ratio of ~2:1. The parameters A and B were determined with the least-squares method from **7** events which were large enough to have been recorded by the USGS network and assigned Richter magnitudes by the California Institute of Technology during the recording period. The magnitudes reported in this study are the averages of estimates from three quietest stations (DP, OB, and WR).

RESULTS

Seismicity. Eight weeks of microearthquake monitoring over the Salton Sea geothermal area revealed that the seismicity was characterized by a combination of sporadic day-to-day activity and intermittent earthquake swarms. Excluding the swarm activity, the microearthquakes appear to occur in groups of three to six events over a time span of $\frac{1}{2}$ to $2\frac{1}{2}$ hr. The epicenters of a given group clustered within 1 km^2; they were uniform in magnitude with no appearance of a typical main shock-aftershock sequence. These groups occur approximately once every other day but the activity at Obsidian Buttes was higher. Many of these events were too weak to be recorded at four or more stations and many records were obscured by cultural noise. All events that were accurately located (RMS $<$ 0.2 sec) are shown in Figure 2.

During the recording period, two swarms occurring within the array were not recorded by the USGS network except by the station at Obsidian Buttes (OBB, Figure 2). The first swarm began at approximately 04:00 UTC on August 12, 1975. The activity was fairly uniform over an 8-hr interval, with 31 events whose magnitudes ranged from 1.0 to 1.5. Eight of these were strong enough to be well recorded and accurately located. The events were centered around 33°0.8.0′N, 115°37.8′W and ranged in depth from 1 to 2.5 km. This swarm ended by a series of sporadic events that were so weak as to have been recorded only at OBB, OB, and WR.

On September 10,1975, at approximately 02:00 UTC, an earthquake swarm began. It included 232 distinct seismic events within 72 hr. The seismogram from station WR (Figure 3) shows examples during period of peak activity. The number of events per hour is shown by a histogram in Figure **4.** The focal depths of the swarm ranged from 0.5 km to 3.5 km with the majority of the hypocenters around 2 km deep. Most of the events were below 1.5 in magnitude. Figure 5 shows *52* events that were large enough to locate accurately. In order to make use of the events recorded at only three stations, the focal depth was fixed at 2 km and epicenter locations were determined for some events. Although not plotted in Figure 5, most of these events fell within the zone clustered by the 52 accurate locations. We attempted to find the patterns of hypocenter migration, but the accuracy of epicenter determination casts some doubt about the deduced pattern because the swarm events clustered in a small area *(2* km by 1 km).

An interesting correlation between focal depth and distance to the geothermal area is shown by a cross section (Figure 6), constructed by projecting the hypocenters into a vertical plane whose surface trace is shown on Figure **2.** The northwest end of the section approaches the center of the geothermal area and the isotherms are shallower there than in the southeast side. The focal depths decrease in general as the epicenters progress toward the northwest. The lower boundary of the foci indicate clearly such a trend.

First motions. A composite first-motion plot for each swarm was constructed from the output of HYP071. The stations are plotted on a lower hemisphere equal-area projection as either a compression or a dilatation. The patterns are then separated into four quadrants assuming a double focal mechanism.

Data from the first swarm are limited, with only three events having clear first motions (Figure **7).** The sparse data do not preclude a reasonable establishment of a first-motion pattern consistent with normal faulting. The two nodal planes trend

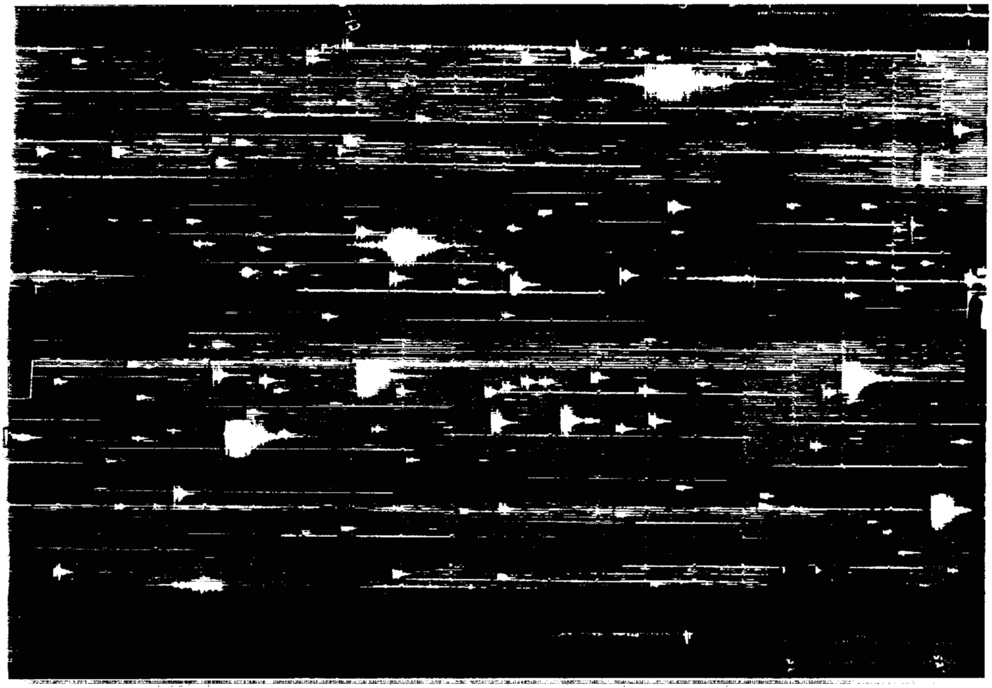

FIG. 3. A seismogram from station WR showing peak activity during the second swarm (started on September 10, 1975). Time interval between tick marks is 20 sec. Signals tapered at both ends were cultural noises.

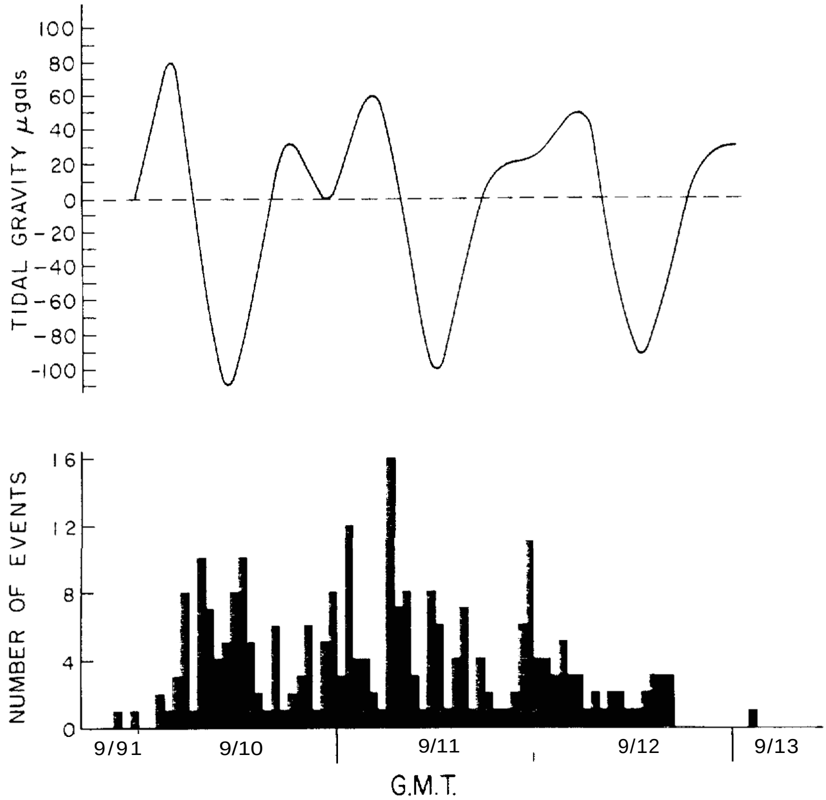

FIG. 4. Comparison of tidal gravity fluctuations with histogram of hourly seismic activity for the second swarm (September 10, 1975).

around N65°E. Although control on the north dipping nodal plane is poor, the other nodal plane which dips approximately 50° south is well constrained. Without additional information, the fault plane cannot be selected.

Figure 8 shows **22** events from the second **swarm** which strongly suggest strike-slip motions on nearly vertical fault planes. There are no surface breaks or other geomorphic features to help in selecting the true fault plane from the two nodal planes. If the fault trends N30°E, it is right-lateral; otherwise, it is left-lateral strike-slip motion along a fault trending N60°W. Epicenter distribution favors the N60°W nodal plane as the fault plane.

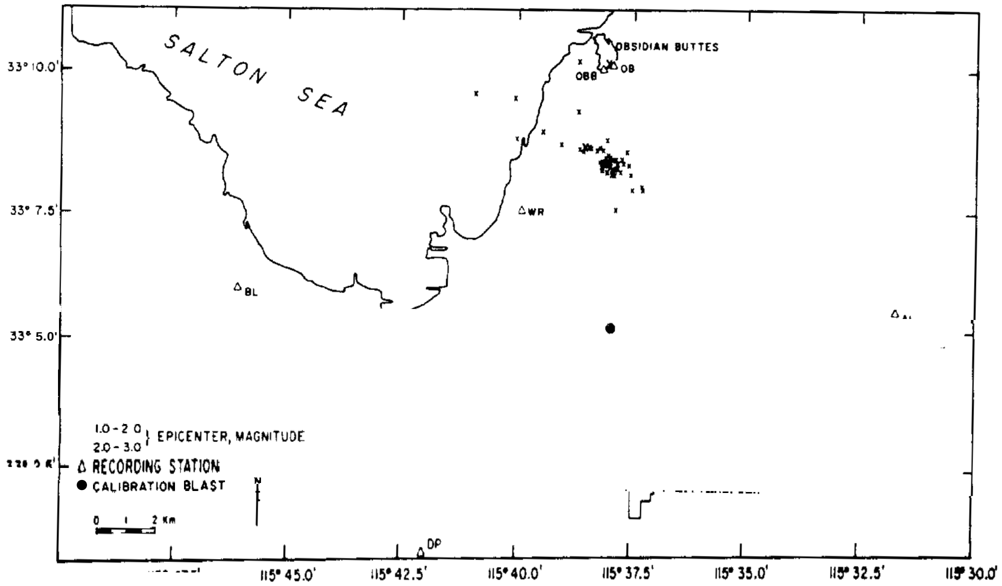

FIG. 5. Epicenter distribution of the second swarm.

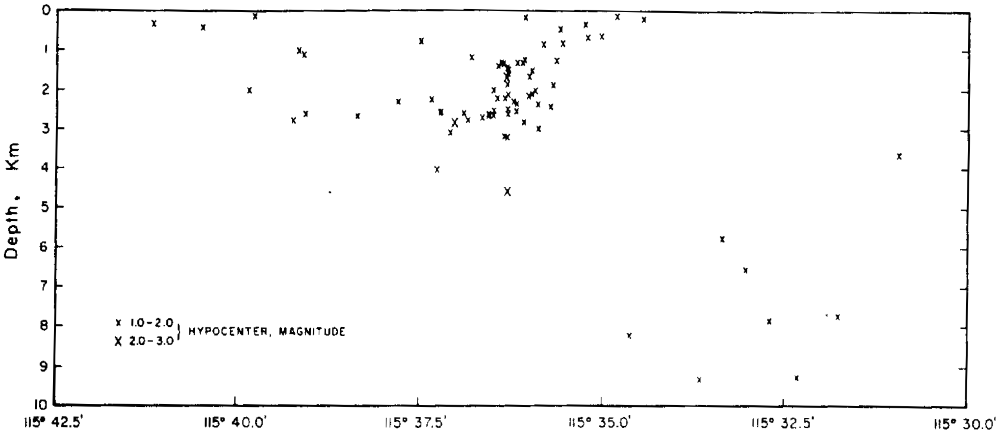

FIG. 6. Cross section showing all hypocenters including swarm data, projected into vertical plane AA′ in Figure 2.

DISCUSSION

The Imperial Valley is tectonically dominated by crustal spreading and right-lateral strike-slip. Regarding the normal faulting and strike-slip motion deduced from the activities of two microearthquake swarms, one may be tempted to make his local faulting models be compatible with the regional tectonics. Because the pattern of first motions is the only available constraint at this stage, the two models discussed below are speculative in nature and differ by the choice of the fault plane of the second swarm (Figure 9).

Fault A trending approximately N50°W (Figure 9) is delineated from epicenters. Fault B running through Obsidian Buttes is primarily located on the basis of past seismicity monitored by the USGS (Hill *et al.*, **1975**). The epicenters of both swarms are confined between these two ***en echelon*** right-lateral strike-slip faults.

Normal faulting as shown by the first swarm indicate crustal extension or spreading between faults A and B. If the nodal plane trending N30°E is chosen as

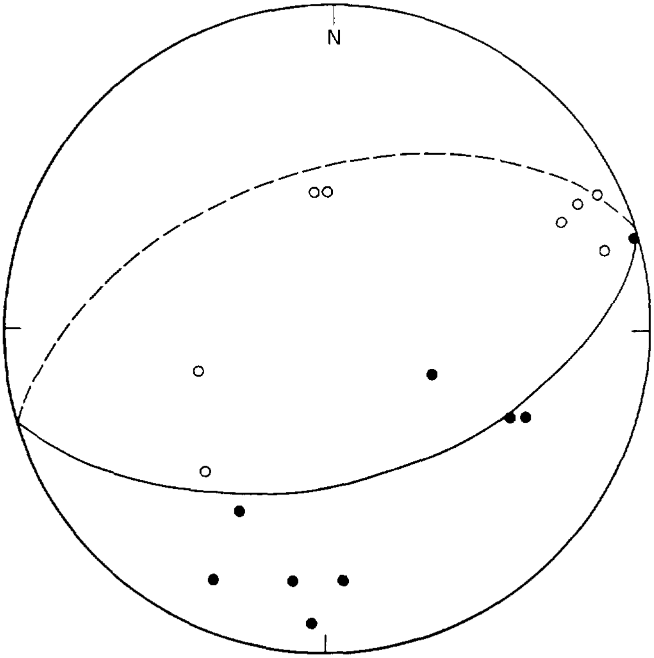

FIG. 7. **Composite first-motion data and fault-plane solution** of **three events** from **the first swarm (August 12, 1975). The open circles represent dilatation and the solid circles represent compression.**

the fault plane for the second swarm, faults A and B may be coupled by a right-lateral strike-slip fault (model *a*). On the other hand, if the alternative is chosen as the fault-plane (trending N60°W), faults A and B may be coupled by a left-lateral strike-slip fault (model ***b***). Both models are consistent with the regional crustal extension and shearing. The area with swarm activity suggests the transfer of right-lateral offset between faults A and B. Perhaps this area marks a leaky transform fault, and faults A and B are two segments of the Brawley fault, previously inferred by Savage ***et al.*** **(1964)** and Hill ***et al.*** **(1975).**

Dislocation model of slip transfer between two ***en echelon*** strike-slip faults has been proposed to explain an earthquake sequence occurring between the San Andreas fault and San Benito fault in central California (Ellsworth, **1975**). Conjugate shear faults may exist locally in an area bound by a pair of ***en echelon*** faults. Even though epicentral distribution favors model ***b*** in the study ***area,*** the possibility of right-lateral shear for the second swarm cannot be precluded because our observation period was limited. Both cases may result in a net extension in the zone between the paired *en echelon* faults. Crustal extension here was evidenced by normal faulting in the observed first swarm but was not observed seismically by Ellsworth (1975) in the Bear Valley.

Tectonic models similar to model *a* have also been proposed for the 1975 Brawley swarm (Johnson and Hadley, 1976) and on a larger scale in the Gulf of California northward through the Salton Trough (Elders *et al.*, 1972). However, there are significant differences in characteristics between the Brawley swarm and the two swarms that occurred south of the Obsidian Buttes, even though the two areas of swarm activities are about 16 km apart. Table 2 summarizes the major differences.

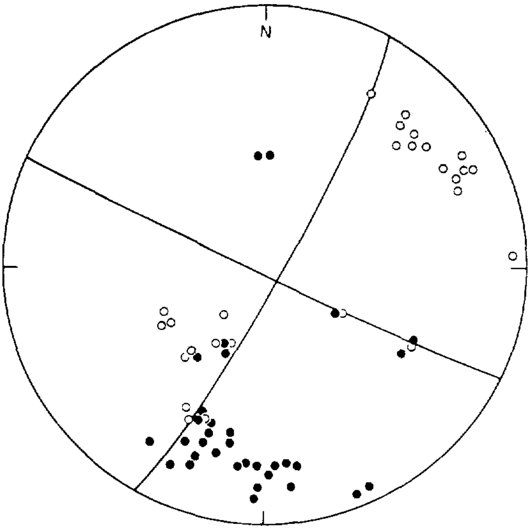

FIG. 8. Composite first-motion data and fault-plane solution of 22 events from the second swarm (September 10, 1975).

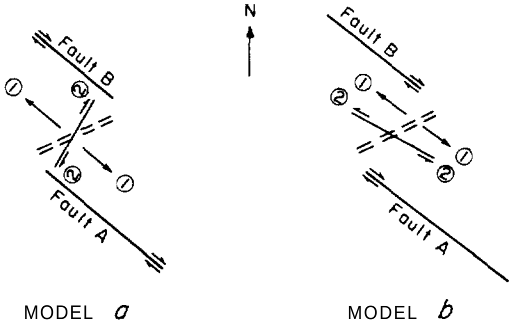

FIG. 9. Leaky transform models between the offset segments (faults A and B) of the previously inferred Brawley fault. Crustal spreading (paired dashed lines) was indicated by normal faulting during the first swarm activity (indicated by 1). In model *a*, crustal shearing was shown by the right-lateral strike-slip during the second swarm activity (indicated by 2). In model *b*, the shearing was left-lateral.

Seismicity in the study area is apparently influenced by the shallower isotherms toward the geothermal area (Figure 6). The reservoir temperatures are 340°C, 200°C, and 180°C at the Salton Sea, Brawley, and East Mesa geothermal areas, respectively (Renner *et al.*, 1975); and the earthquake foci were at depths around 2 km, 6 km (Johnson and Hadley, 1976), and 5 km (Combs and Hadley, 1977) at the corresponding areas. Crustal motion in the Salton Trough are taken up as stable sliding (aseismic creep) in the relatively higher temperature regime but in the upper part of the geothermal area, the sediments or metasedimentary rocks still remain brittle enough to reflect the spreading by normal faulting and the shearing by strike-slip faulting.

Hill (1977) has proposed a geometric model to explain swarm activities. Shear failure occurs when fluid pressure or the difference between the greatest and the least principal stresses has reached a critical value. Swarm activities propagate outward from the focus of the initial event until the affected volume has adjusted itself through shear failures to a state below the critical value. Some earthquake swarms may hence be triggered by the Earth tide which affects the stress-strain state. Because we are unable to determine the migration of foci with confidence, Hill's model cannot be tested here.

Sauck (1975) reports a positive correlation between the Earth tidal gravity fluctuation and the microearthquake activity of the 1975 Brawley swarm. He concludes that in studies involving large numbers of events on a global scale, poor correlation is expected and that good correlations have been found for limited sequences of events associated with smaller zones or specific faults. Consequently, we examine the relation between the tidal fluctuation and the second swarm activity. A histogram of the number of events per hour from the second swarm was constructed and cross-correlated with the tidal gravity fluctuations (Figure 4). The two sets of data were first normalized and cross correlation coefficients were then calculated. The results showed poor correlation with a correlation coefficient of 0.16 for zero time lag. Even after simple three and five point smoothing formulas were applied to the histogram the correlation coefficients were only 0.23 and 0.25, respectively. It can thus be stated that for the microearthquake swarm which occurred on September 10, 1975, there is no correlation between tidal gravity fluctuations and microearthquake activity. From analyses of tidal stress at the time of earthquakes, and considerations of dilatancy-diffusion model, Heaton (1975) concludes that tidal triggering should not have been seen for small magnitude shallow dip-slip or strike-slip earthquakes.

TABLE 2

COMPARISON OF EARTHQUAKE SWARMS NEAR BRAWLEY AND SALTON SEA GEOTHERMAL AREA

	1975 Brawley Swarm*	Salton Sea
Epicenter migration	Bilateral at 0.5 km/hr from initial epicenter	Not decipherable
Magnitude M_L	75 events between 3.0 and 4.7 in 4 days	Below 1.5
Focal depth	4 to 8 km	0.5 to 3.5 km
Areal distribution of epicenters	12 km x 3 km	2 km × 1 km
Fault-plane solution	Normal faulting, thrust, and right-lateral strike-slip	Normal faulting and strike-slip with sense of offset undetermined
Earth tide	Correlatable†	Not correlatable

* From Johnson and Hadley (1975).

† Excerpt from Sauck (1975).

CONCLUDING REMARKS

Earthquake foci in the Salton Sea geothermal area are unusually shallow (1 – 3 km) compared to foci at the rest of the Imperial Valley. Crustal spreading and shearing in the Salton Trough appear probably as stable sliding (aseismic creep) in the relatively higher temperature regime but in the upper part of the geothermal area, the meta-sedimentary rocks still remain brittle enough to reflect the spreading by normal faulting and the shearing by strike-slip faulting. Two swarms marked the site of a leaky transform fault that transfers the offset of the Brawley fault which was previously inferred to have extended northward from Brawley through the Obsidian Buttes without any appreciable offset.

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