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EARTHQUAKE SWARM IN THE SANTA BARBARA CHANNEL, CALIFORNIA, 1968

ARTHUR G. SYLVESTER, STEWART W. SMITH,* AND C. H. SCHOLZ†

ABSTRACT

Sixty-three minor earthquakes (maximum magnitude = 5.2) occurred in the Santa Barbara Channel during the period June 26 to August 3 1968. The epicenters form a shot-scatter pattern upon a broad, high-standing fault block in the channel midway between Santa Cruz Island and the City of Santa Barbara. Focal mechanism studies indicate that oblique-slip movement occurred along a northwest-striking fault even though the major folds and faults strike nearly east-west. Preliminary studies of the areal hydrocarbon production data show no compelling evidence for a causal relationship with the swarm.

INTRODUCTION

The series of earthquakes that shook the Santa Barbara Channel and adjacent mainland and islands areas in the summer of 1968 comprised an *earthquake swarm*, in that no single shock predominated among the long series of minor shocks. The event is noteworthy, because swarms are not common in southern California, having only been documented previously in the Imperial Valley at the southern end of the San Andreas fault system (Richter, 1958, p. 72), and at Walnut near Pomona (Richter and Gardner, 1960).

REGIONAL STRUCTURAL SETTING

The Santa Barbara Channel is the seaward extension of the western Transverse Ranges (Figure 1), a geological province characterized by a system of high-angle, east-west to west-northwest striking faults which some writers consider to be conjugate to the northwest-striking San Andreas and related fault zones (Hill and Dibblee, 1953). The major faults in the channel region also strike east-west and west-northwest. On the mainland and the islands they are oblique-slip faults, and left-lateral horizontal components of displacement have been determined for some of them as follows: Santa Ynez fault—more than 27 km since the Eocene (Page and others, 1951); Santa Rosa Island fault—as much as 30 km since the lower Miocene (Weaver, 1969); Santa Cruz Island fault—at least 18 km (Harrison and others, 1966). The ratio of the strike-slip components to the dip-slip ranges from 7:0 to 10:1.

Minor northwest- and northeast-striking faults have been mapped on the Channel Islands (Weaver, 1969), on the channel floor (Vedder and others, 1969, their Plate 1) and on the mainland (Dibblee, 1950; 1966).

Gravity and magnetic data provide information on the deep structure of the channel. A major gravity and magnetic ridge trends N25–30°W from the center of Santa Cruz Island into the middle of the channel (von Huene and Ridlon, 1966). This ridge may be

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* Present address: Geophysics Program, University of Washington, Seattle, Washington.
† Present address: Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.

the northwest end of an even greater gravity and topographic ridge more than 250 km long in the central part of the southern California continental borderland (Harrison and others, 1966). The presence of the ridge in the channel is of particular interest because it is close to the epicentral area of the 1968 earthquake swarm, and its trend is consistent with one of the focal mechanism solutions as described below; however, the structural character of the anomaly is not known (von Huene, written communication, 1969).

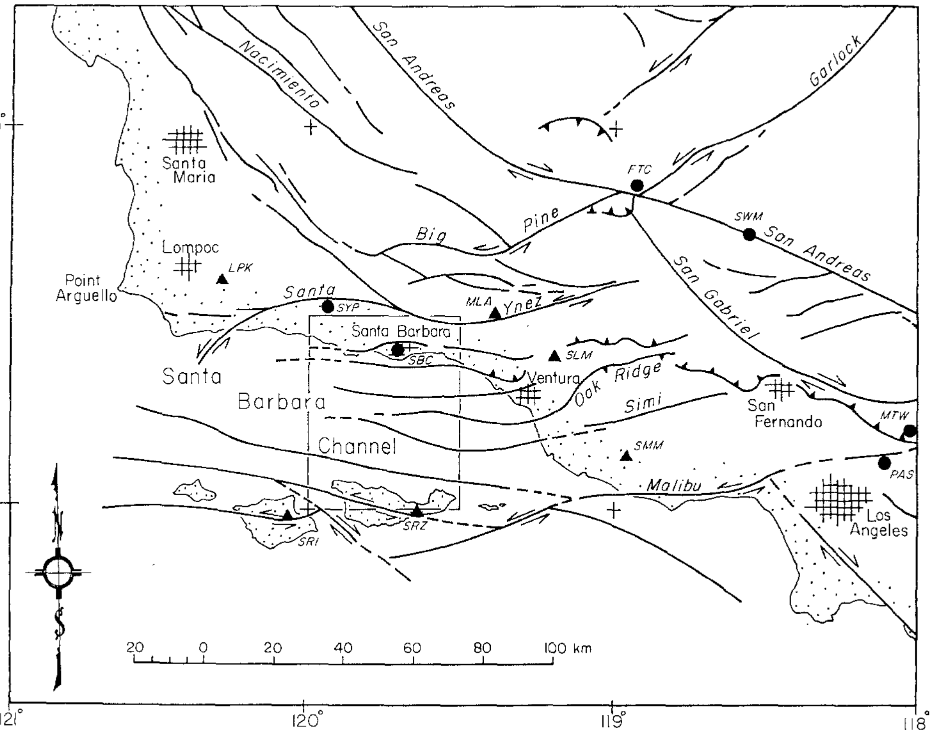

FIG. 1. Index map showing the geometry of the principal east-west trending faults of the Transverse Range province and the northwest-southeast trending faults of the San Andreas system. The *rectangle* encloses the area shown in Figure 2. Locations of permanent seismograph stations of the Caltech Seismological Laboratory network are shown in *solid dots*. Portable stations established during the 1968 swarm are shown in *black triangles*.

SEISMIC HISTORY OF THE SANTA BARBARA CHANNEL

There are four noteworthy seismic events in the historic record of earthquakes in the channel area (see also Hamilton and others, 1969, and their Table 3):

December 21 1812. Intensity = X (?); epicenter presumed to have been in the Santa Barbara Channel; destroyed or damaged missions from Lompoc to San Fernando; generated a tsunami which may have run up as much as 0.5 mile along parts of the Santa Barbara coastline (Grazzinif and others, in press).

June 29 1925. Magnitude 6.3; epicenter in the Santa Barbara Channel; $20,000,000 damage in Santa Barbara and outlying areas (Willis and others, 1925; Kirkbride, 1927).

November 4 1927. Magnitude 7.5; epicenter on a submarine fault 70 km west of Pt. Arguello; generated a tsunami from 5 to 7 feet ($1\frac{1}{2}$ to $2\frac{1}{2}$ m) high at the nearest coastline (Byerly, 1930). Several moderate earthquakes (maximum magnitude = 5.8) occurred in the same general vicinity in October and November 1969. Although the epicenters of the shocks cannot be located accurately, it appears likely that the activity probably occurred on the same fault system as that in 1927.

June 30 1941. Magnitude 5.9; epicenter in the Santa Barbara Channel; $100,000 damage in Santa Barbara, chiefly to structures weakened and inadequately repaired after the 1925 earthquake (Richter, 1958, p. 534).

Several series of minor earthquakes are listed in the historic record (Townley and Allen, 1939) which appear to have been similar to the 1968 swarm with respect to the number and intensity of felt shocks and to the duration of each series. These inferred swarms, which appear to be discrete events rather than foreshock or aftershock sequences, are listed in Table 1.

TABLE 1

POSSIBLE HISTORIC EARTHQUAKE SWARMS IN THE SANTA BARBARA CHANNEL*

Year	Month and Day	Number of Felt Shocks	Intensity† of Strongest Shock
1815	January 18	5	
	January 30	"More"	
1815	July 8, 9	6	
1854	April 20	1	
	April 29	1	III
	May 3	3	V
	May 13	1	
	May 29	1	
	May 31	3	VI
1909	July 2	1	
	July 4	1	III
	July 16	1	
	July 31	1	IV?
1920	January 30	7	III
1929	July 3	2	
	July 16	1	
	August 28	1	
	September 8	1	

* Compiled from Townley and Allen, 1939 and Seismological Notes for 1929, *Bull. Seism. Soc. Am.*).

† Intensities are given for Santa Barbara.

INSTRUMENTAL DATA

Sixty-three shocks were recorded on permanent seismographs at Santa Ynez Peak and Santa Barbara Museum of Natural History during the period June 26 to August 3 1968. Four portable seismograph stations were established around the channel on July 5 1968 after the largest event of the swarm. Hypocentral data for the individual shocks are listed in Table 2 and their epicenters are plotted in Figure 2. Data for all earthquakes (seven only) which occurred during the year prior to the first shock of the swarm are also listed and plotted. Twenty-two of the swarm earthquakes were strong enough to be felt in the Goleta Valley-Santa Barbara area, and of these shocks three

TABLE 2

INSTRUMENTAL DATA FOR 1968 SWARM AND FOR ALL EARTHQUAKES (SEVEN ONLY) IN THE AREA DURING THE YEAR PRIOR TO THE INITIATION OF THE SWARM

Year	Month	Day	Hour	Min	Seconds	Latitude	Longitude	Q	Magnitude	Depth	S
1967	07	02	06	41		34 23	119 30		2.5		
1967	08	13	12	52		35 26	120 00		3.8		
1968	04	09	05	30		34 20	119 51		2.8	12.0	
1968	04	10	02	47		34 24	119 49		1.5	14.0	
1968	04	12	12	47		34 21	119 50		2.4	16.0	
1968	06	12	03	16		34 24	119 50		2.5		
1968	06	13	14	15		34 21	119 51		2.5		
1968	06	26	18	11	11.23	34 12.74	119 41.49	B	4.0	13.9	1A
968	06	26	18	11	Felt Santa Barbara, Goleta, Oxnard						
1968	06	26	18	13	54.79	34 13.11	119 38.56	B	3.0	3.4	1A
1968	06	26	18	18	33.98	34 11.44	119 40.41	B	2.8	2.0	1A
1968	06	26	21	42	31.47	34 12.96	119 41.12	B	3.8	13.0	1A
968	06	26	21	42	Felt Santa Barbara						
1968	06	26	22	06	23.86	34 15.81	119 36.79	B	2.9	2.2	1A
1968	06	26	22	41	24.81	34 13.22	119 39.32	B	3.0	1.3	1A
1968	06	26	23	01	51.05	34 14.30	119 38.50	B	2.9	1.0	1A
1968	06	29	00	09	46.91	34 14.39	119 35.97	B	3.1	−2.0	1A
968	06	29	00	09	Felt Santa Barbara						
1968	06	29	06	33	20.91	34 10.98	119 38.76	B	4.0	8.4	1A
968	06	29	06	33	Felt Santa Barbara						
1968	06	29	06	47	49.49	34 12.80	119 37.36	B	3.1	−0.8	1A
968	06	29	15	32	42.81	34 14.98	119 39.23	B	4.1	14.6	1A
1968	06	29	15	32	Felt Santa Barbara, Goleta, Carpinteria						
1968	06	29	15	38	21.50	34 12.58	119 40.39	B	3.3	4.7	1A
1968	06	29	15	53	56.87	34 08.58	119 37.14	B	3.4	8.0	1A
968	06	29	15	53	Felt Santa Barbara						
1968	06	29	16	11	24.39	34 10.37	119 40.14	B	3.3	4.2	1A
1968	06	29	19	12	21.32	34 15.16	119 41.90	C	4.2	9.5	1A
968	06	29	19	12	Felt Santa Barbara, Goleta, Carpinteria						
1968	06	29	19	13	57.00	34 16.00	119 34.00	C	4.4	10.0	1A
968	06	29	19	13	Felt Santa Barbara, Goleta, Carpinteria, Lompoc, Santa Ynez, Cachuma						
1968	06	29	19	21	50.76	34 14.16	119 37.17	B	3.5	−2.0	1A
968	06	29	19	21	Felt Santa Barbara						
1968	06	29	20	36	33.62	34 14.68	119 35.28	B	4.0	1.8	1A
968	06	29	20	36	Felt Santa Barbara, Goleta						
1968	06	29	22	13	02.21	34 12.76	119 40.54	B	3.4	−2.0	1A
1968	06	29	22	45	08.56	34 10.98	119 37.96	B	3.3	−2.0	1A
1968	06	29	23	11	53.17	34 13.32	119 39.27	B	3.3	−0.1	1A
1968	06	29	23	48	55.56	34 13.48	119 39.01	B	3.7	0.8	1A
1968	06	30	08	06	00.18	34 12.66	119 35.92	B	3.2	−0.9	1A
1968	07	01	02	26	43.60	34 11.89	119 40.01	B	3.5	−2.0	1A
1968	07	02	03	20	02.56	34 12.75	119 43.15	B	3.5	1.9	1A
968	07	02	03	20	Felt Goleta						
1968	07	02	15	42	57.45	34 11.45	119 41.09	B	3.2	−1.6	1A
1968	07	04	22	15	56.24	34 14.43	119 40.32	B	3.1	−2.0	1A
1968	07	05	00	36	06.43	34 11.55	119 43.99	B	4.0	15.6	1A
968	07	05	00	36	Felt Santa Barbara, Goleta						
1968	07	05	00	45	17.22	34 07.06	119 42.15	B	5.2	5.9	1A
1968	07	05	00	45	Felt over 8,000 square-mile area from Seal Beach to Taft to Guadalupe. Maximum intensity VI at Goleta, Santa Barbara, Carpinteria.						
1968	07	05	02	09	09.77	34 11.39	119 41.14	B	2.9	3.1	1A

TABLE 2—*Continued*

Year	Month	Day	Hour	Min	Seconds	Latitude	Longitude	Q	Magnitude	Depth	S
1968	07	05	02	36	14.12	34 04.33	119 43.37	B	4.0	4.3	1A
968	07	05	02	36	Felt Santa Barbara						
1968	07	05	04	18	35.99	34 14.81	119 40.89	C	3.5	13.3	1A
968	07	05	04	18	Felt Goleta						
1968	07	05	05	28	25.70	34 13.76	119 39.10	B	3.4	8.0	1A
968	07	05	05	28	Felt Santa Barbara						
1968	07	05	06	16	55.44	34 16.29	119 42.13	B	3.3	11.8	1A
1968	07	05	09	32	46.75	34 16.13	119 40.81	B	3.7	13.2	1A
968	07	05	09	32	Felt Goleta, Santa Barbara						
1968	07	05	15	03	09.83	34 16.03	119 42.56	B	3.5	10.7	1A
968	07	05	15	03	Felt Goleta, Santa Barbara						
1968	07	05	18	33	09.77	34 11.32	119 41.00	B	3.3	1.8	1A
1968	07	05	18	44	56.36	34 09.29	119 41.60	B	3.0	3.5	1A
1968	07	06	01	11	25.65	34 10.11	119 42.86	B	3.1	−1.6	1A
1968	07	07	04	56	03.57	34 10.52	119 38.40	B	3.3	5.8	1A
1968	07	07	05	27	22.17	34 05.68	119 39.29	B	3.5	3.7	1A
1968	07	07	14	33	30.76	34 10.57	119 45.27	B	4.5	12.8	1A
968	07	07	14	33	Felt Goleta, Santa Barbara						
1968	07	07	16	22	40.44	34 13.52	119 45.79	B	3.3	12.1	1A
1968	07	07	20	30	40.80	34 12.40	119 38.27	B	3.3	8.9	1A
1968	07	08	08	22	29.49	34 16.64	119 38.07	B	3.6	17.5	1A
968	07	08	08	22	Felt Santa Barbara						
1968	07	08	09	06	12.89	34 16.46	119 38.39	B	3.6	14.9	1A
968	07	08	09	06	Felt Goleta, Santa Barbara						
1968	07	08	09	18	37.18	34 15.26	119 37.70	B	4.0	15.7	1A
968	07	08	09	18	Felt Goleta, Santa Barbara						
1968	07	08	15	55	58.53	34 15.78	119 38.65	B	2.9	11.9	1A
1968	07	08	15	56	49.19	34 17.22	119 36.92	B	3.1	13.1	1A
1968	07	08	23	58	48.18	34 11.21	119 37.82	B	3.2	5.9	1A
1968	07	09	05	40	49.96	34 16.00	119 37.30	B	3.3	16.0	1A
968	07	09	05	40	Felt Santa Barbara						
1968	07	09	19	13	19.42	34 13.62	119 41.74	B	3.1	1.0	1A
1968	07	10	08	14	08.81	34 13.51	119 40.72	B	3.2	8.7	1A
1968	07	10	21	49	26.57	34 14.50	119 41.00	B	3.6	12.0	1A
968	07	10	21	49	Felt Santa Barbara						
1968	07	11	19	29	24.72	35 22.38	118 30.25	B	3.0	9.1	1A
1968	07	12	20	59	18.86	34 14.74	119 43.15	C	3.2	15.0	1A
1968	07	14	12	40	28.63	34 14.00	119 40.85	B	3.7	15.0	1A
1968	07	30	06	03	15.56	34 15.99	119 38.28	B	3.6	16.1	1A
968	07	30	06	03	Felt Santa Barbara						
1968	07	30	19	11	48.72	34 15.44	119 39.03	B	3.4	17.4	1A
1968	07	31	10	08	12.26	34 16.33	119 37.98	B	3.0	16.4	1A
1968	07	31	10	10	51.94	34 17.03	119 37.35	A	3.1	16.1	1A
1968	07	31	12	19	43.69	34 13.50	119 34.68	B	3.6	−2.0	1A
968	07	31	12	19	Felt Santa Barbara						
1968	07	31	22	44	45.31	34 15.29	119 36.84	A	4.0	15.0	1A
968	07	31	22	44	Felt Santa Barbara						
1968	08	03	12	55	03.27	34 14.37	119 35.31	B	3.0	7.7	1A

were strong enough to cause approximately $12,000 damage in Goleta. These shocks and related damage are summarized in Table 3, and their epicenters are designated in Figure 2*a*. An isoseismal map for the July 5 shock (ESSA, 1969, p. 11) is almost identical in style to those for two minor earthquakes in April 1917 (Mattei, 1917).

The error associated with the locations of individual epicenters is believed to be about 3 km, but it may be considerably more inasmuch as the deep crustal velocity profile has not been adequately documented in the channel region, and the azimuthal distribution of seismographs was not optimal during most of the events of the swarm. Installation of portable stations (Figure 1) increased the precision of locating epicenters, but the distribution of epicenters for earthquakes during operation of the portables is virtually the same as that prior to their installation. The focal depths given in Table 2 vary from the top of the sea floor to 17.4 km, but they may have a large margin of error for the same reasons.

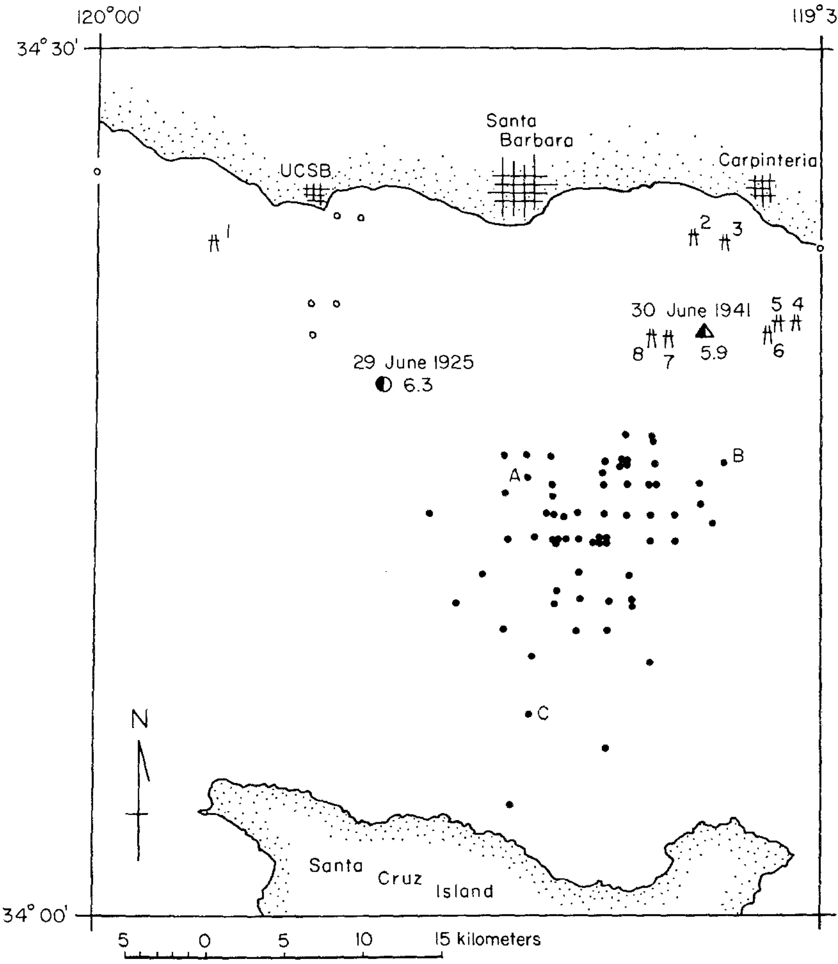

FIG. 2*a*. Epicentral map of the 1968 swarm (*solid dots*). *Open circles* are for shocks recorded in the year prior to the swarm. *A* = June 29 1968, 1912 hr, magnitude 4.2; *B* = June 29 1968, 1913 hr, magnitude 4.4; *C* = July 5 1968, 0045 hr, magnitude 5.2. Oil well drilling platforms: (*1*) Holly; (*2*) Hilda; (*3*) Hazel; (*4*) Heidi; (*5*) Hope; (*6*) Hogan; (*7*) Platform A (erected after cessation of the swarm); (*8*) Platform B (also erected after cessation of the swarm). The error of epicentral locations is probably more than 3 km.

DISTRIBUTION OF EPICENTERS AND CORRELATION WITH GEOLOGICAL STRUCTURES

The distribution of epicenters is evidently random as is shown in Figure 2*a*, although a vague N5–10°E trend may be discerned. Systematic attempts were made to identify consistent spatial and temporal patterns among the shocks with respect to such parameters as magnitude and geological structure. Except for the fact that the strongest shocks are also the deepest, no patterns emerged that either differ significantly from that for all of the epicenters or correlate consistently with the available geological data.

The epicenters are clustered upon a broad high-standing fault block (the Montalvo trend of Weaver, 1969), that trends and plunges gently west-northwest (Figure 2*b*). The fault block appears to be structurally similar to those along the same trend on the mainland in that it is bounded by major high-angle reverse faults, each of which parallels the trend of the block and dips steeply toward the other bounding fault. Other minor subparallel faults occur at structurally higher levels in the block. The epicenters of the two strongest shocks of June 29 plot on the submarine extension of the Oak Ridge fault, and the $M = 5.2$ shock of July 5 plots very near the trace of a major west-northwest striking fault approximately 7 km north of Santa Cruz Island.

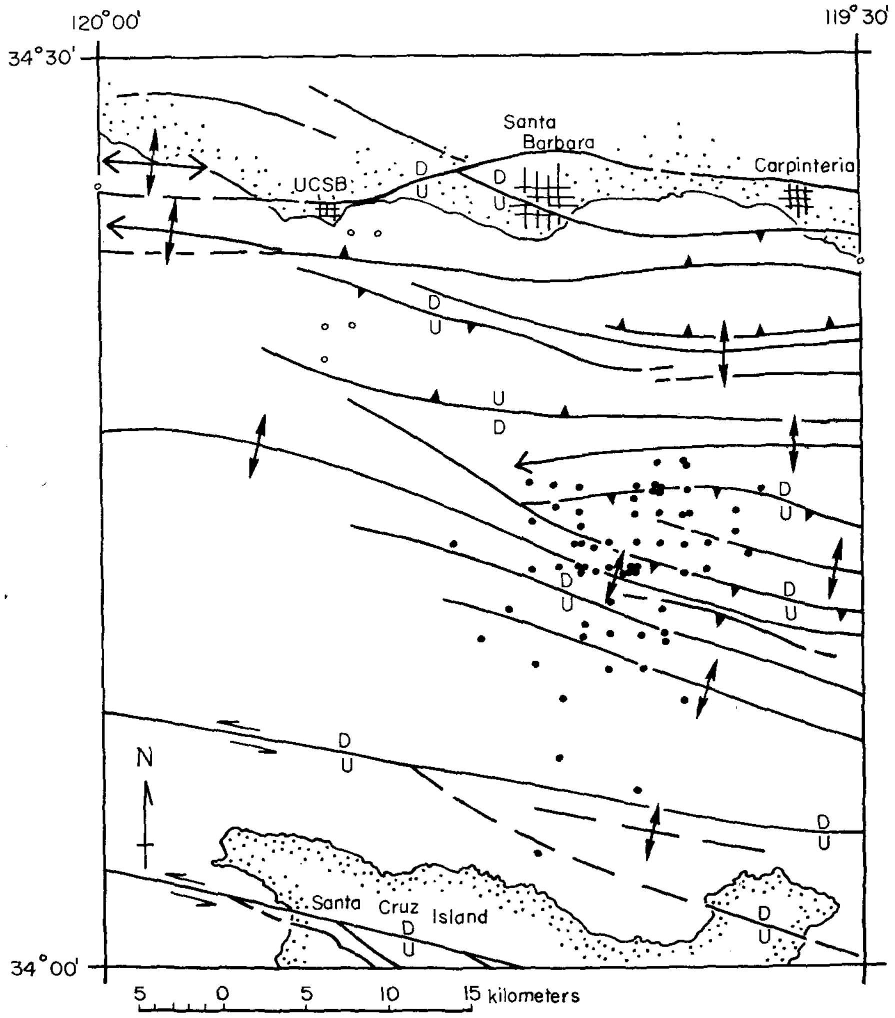

FIG. 2*b*. Epicentral data of the 1968 swarm superimposed upon the structural framework of the Santa Barbara Channel (after Weaver, 1969). The epicenters are clustered upon a broad, east-west trending high-standing fault block.

In view of the uncertainty of the magnitude of error in determining epicentral and hypocentral locations of these shocks, we conclude that additional statements on the spatial distribution of shocks and their correlation with geological structures in the channel would be speculative and not warranted until more accurate data are obtained for the deep crustal velocities in this area and are used to redetermine the earthquake locations.

Focal Mechanism

An attempt was made to determine the fault parameters for some of the events of the swarm. Several shocks with magnitudes close to 4.0 occurred after installation of the portable stations, and good azimuthal coverage was available. The frequency response chosen was peaked at 25 cps owing to the high level of microseisms on the island and coastal seismograph sites. With this response and magnifications of the order of 100,000, very clear first motions were discernible on shocks in the magnitude range of 3.0 to 4.0 out to distances of approximately 100 km. At these short ranges and without teleseismic data, one can make a local first-motion map and determine the nodal planes simply by plotting observed polarities directly on the map. However, the simple separation of domains of compression and dilatation by two straight lines is complicated by polarity reversals which may occur for a refracted arrival when the take-off angle exceeds the dip of the fault. In the southern Coast Ranges the wave refracted from near the base of the crust (P_n) is the first arrival on seismograms at distances of approximately 100 km (Healy, 1963). For stations east of the Santa Barbara region the appearance of the seismograms confirms this observation. West of Santa Barbara, however, polarity reversals occur at distances as near as 60 km in a fashion that can be explained only by inferring the presence of a steeply dipping refracting horizon. Thus, polarity reversals of this nature complicate the determination of the focal mechanism for the small shocks which characterize this swarm.

Eight earthquakes (Table 5) were located well enough, and had sufficient azimuthal coverage to justify a focal mechanism solution, and all of these events are consistent

TABLE 3

Data Pertaining to the Three Strongest Shocks of the 1968 Earthquake Swarm

Date and Time (GCT)	Magnitude (Richter)	Intensity* (R.F.)	Damage and Related Phenomena
29 June 1912 1913	4.2 4.4	IV IV–VI	Considered as one shock for interview purposes. North-south "bump," followed almost immediately by east-west shaking. $2,000 damage, primarily to shelved merchandise in Goleta grocery stores, some of which are known to be constructed on a foundation of water-saturated soil
5 July 0045	5.2	V	North-south "bump," followed almost immediately by east-west shaking. $10,000 in Goleta: broken plate glass windows, spillage and breakage of shelved merchandise in some of the same stores affected on 29 June; accoustical tile and fluorescent light fixtures fell or became detached in at least two grocery stores and a library adjacent to one of the stores. Some loss of shelved merchandise in Carpinteria

* Intensities pertain to Goleta.

with movement along northwest or northeast striking fault planes (Figure 3, *a* and *b*). The domains of compression and dilatation are separated by the traces of the fault and auxiliary planes where direct P is the first arrival. Where P_n is a first arrival, compression and dilatation are separated by the trace of the intersection of the fault plane and the vertical cone of downgoing P_n waves from the hypocenter, and by arcs of circles at the critical distance as is explained in the figure caption. The Lompoc (*LPK*) station is inconsistent with the solution illustrated in Figure 3*a*, but small changes in the hypocentral location or the dip of the northwest fault plane might extend the arc of the circle shown near the *LPK* station, and bring it into agreement with the general solution. However, where the location and depth are determined assuming a homogeneous velocity distribution, we have not been able to find a solution for which the three stations *LPK*, *SYP* and *SBC* are consistent. The possibility that one of the stations had reversed polarity was eliminated by comparison of P waves from teleseismic events. The solution displayed in Figure 3*a* seems to be the most reasonable one, and as men-

TABLE 4

DATA PERTAINING TO OFFSHORE OIL OPERATIONS IN THE SANTA BARBARA CHANNEL[a]

Platform	Operator	Approximate Data Production Commenced	Production as of August 26 1968[b]
Hazel	Standard	November 1959	4,000 bbl/day oil 4,000 bbl/day water
Hilda	Standard	January 1960	
Holly	Atlantic-Richfield	January 1960	not available
Hope	Standard	January 1966	9,000 bbl/day oil 3,500 bbl/day water
Heidi	Standard	June 1966	
Hogan	Phillips	June 1968	10,000 bbl/day oil 4,000 bbl/day water (7,000 bbl/day oil 29 July 1968)

[a] U. S. Coast Guard, personal communication.

[b] All figures are approximate.

TABLE 5

INSTRUMENTAL DATA USED FOR FOCAL MECHANISM STUDIES

Year	Month	Day	Hour	Min	Seconds	Latitude	Longitude	Q	Magnitude	Depth	S
List 1. Six consistent earthquakes plotted in Figure 3a.											
1968	07	09	05	40	49.96	34 16.00	119 37.30	B	3.3	16.0	1A
1968	07	10	08	14	08.81	34 13.51	119 40.72	B	3.2	8.7	1A
1968	07	10	21	49	26.57	34 14.50	119 41.00	B	3.6	12.0	1A
1968	07	12	20	59	18.86	34 14.74	119 43.15	C	3.2	15.0	1A
1968	10	28	20	32		34 13.10	119 42.80			R	
1968	11	06	08	03	27.80	34 12.00	119 42.30			R	
List 2. Two consistent earthquakes plotted in Figure 3b.											
1968	07	14	12	40	28.63	34 14.00	119 40.85	B	3.7	15.0	1A
1968	11	17	15	49		34 11.00	119 50.00			R	

tioned above changes in the velocity structure that may be expected in this transition region between ocean and continent might well bring the *LPK* data into agreement.

Six of the events require that a nodal line pass between Santa Barbara (*SBC*) and Santa Ynez Peak (*SYP*) (Figure 3*a*). The resulting nodal planes are N30°W dipping 80°SW and N40°E dipping 45°SE (Figure 3*a*). The other two events require that the

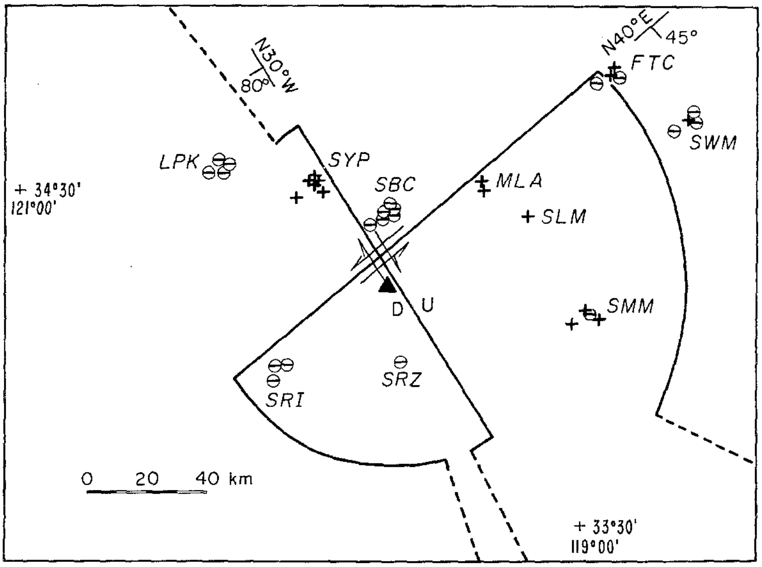

FIG. 3*a*. Composite local first motion map for six consistent earthquakes assuming a focal depth of 10 km. The location of the epicenter is shown by the *solid triangle*. The traces of the nodal planes are shown by *heavy lines*, and the *dashed lines* represent the intersection of these planes with the cone of downgoing P_n waves from the hypocenter. Where P_n is a first arrival these dashed lines will separate regions of compression and dilatation. The *arcs of circles* represent the critical distance for P_n in those regions where P_n will have a different first motion than direct P.

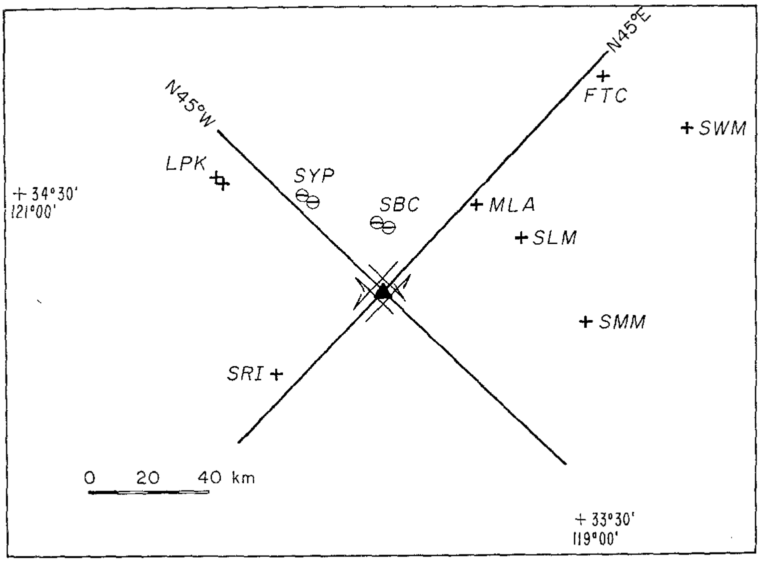

FIG. 3*b*. Composite local first-motion map for two consistent earthquakes. The location of the epicenter is shown by the *solid triangle*. Solution is for strike-slip faulting on vertical planes; thus the trace of fault and auxiliary planes define regions of compression and dilatation for both P_n and direct P.

northwest-trending nodal line be slightly farther west of north and pass between *LPK* and *SYP* (Figure 3*b*). The resulting solution is for pure strike-slip motion on vertical fault planes oriented either N45°W or N45°E. The two solutions are thus most closely consistent with one another if a single fault plane is chosen to be near vertical and striking northwest. This means that the motion would be right-slip in both cases, but there is also a significant dip-slip component in the case of the six events shown in Figure 3*a*.

It is interesting to note that Gutenberg (1941) shows that all of the instrumentally determined shocks (nine) in the channel up through 1941 had dilatational first motion at Santa Barbara and compression at Pasadena and Mount Wilson. One of these earthquakes was the magnitude 5.9 event of 1941. The locations for these earthquakes are not close enough to the swarm under study that they can be included in a composite first-motion plot; however, they are all in rough agreement with right-slip motion on a northwest-striking fault.

Discussion

The earthquake swarm provides two lines of evidence about active faulting in the Santa Barbara Channel: the distribution of epicenters, and the first motion patterns. The epicenters are distributed in the center of the channel upon a broad high-standing block bounded by steep east-west and west-northwest striking faults. They also plot close to the trace of a northwest-trending gravity and magnetic anomaly which may be the manifestation of a deep structure penetrating beneath the east-west structures of the channel from the continental borderland region south of the islands. The hypocentral and epicentral data do not permit a clear choice between these two differently trending systems because of errors which preclude identification of the fault, or faults, along which movement occurred.

Nordquist (personal communication, 1968) pointed out that the vague N5–10°E trend of epicenters is perpendicular to the surface traces of major channel faults. He suggested that such a transverse epicentral alignment may indicate movement on a deep N5–10°E striking fault, whereas any movement on surficial faults is secondary. This is analogous to the explanation proposed by Richter and Nordquist (1951) for the Manix, 1947, earthquake, and the phenomenon has been discussed more fully by Richter (1969). Our focal mechanism studies, however, are not consistent with movement on a fault striking nearly north-south.

The focal mechanism studies indicate that movement occurred along a nearly vertical northwest-striking fault, and that the sense of movement was oblique with a right-slip component of horizontal movement. This solution is geometrically and kinematically consistent with the current pattern of faults and faulting elsewhere in southern California (Allen and others, 1965) and the continental borderland (Albee and Smith, 1966). The solution is not consistent, however, with the east-west strike and left-slip displacement postulated for the major faults in the channel.

We postulate that the inconsistency between the focal mechanism solution and the surface and near-surface geological data may be resolved by one, or a combination of, the following hypotheses which we are currently testing in more detail:

(1) If the western Transverse Ranges are kinematically and dynamically consistent with the rest of southern California, then strike-slip movement would now be precluded on the east-west channel faults, and one must postulate that movement is occurring on new, or previously unrecognized northwest-striking faults.

(2) It is possible that the earthquakes occurred along a deep (10 to 20 km) north-

west-striking structure (von Huene and Ridlon, 1966) which has no surface expression or obvious tectonic relationship to the shallower east-west structures. Such a difference in the orientation of deep and shallow structures does not necessarily imply a major difference in the orientations of the principal axes of stress, because as has often been pointed out: "a fault, once established, is a plane of weakness, and . . . later movements are not simply related to the principal stress directions" (McKenzie, 1969).

(3) It is also possible that the western Transverse Ranges are *not* kinematically and dynamically consistent with the rest of southern California, or at least the strain-stress patterns are different from those which obtained during the Pliocene and Pleistocene when left-slip movement occurred along many of the faults in the channel region. Richter (1969) has described several examples in which significant regional and local changes in the stress field may have occurred after formation of a fault.

Relationship to Hydrocarbon Exploration and Withdrawal

Offshore oil-well platforms, which were erected prior to the swarm and were producing hydrocarbons, chiefly crude oil, are shown in Figure 2*a*. Pertinent data relating to their operations as of August 26 1968 are given in Table 4. According to company officials, production was in no way affected by the earthquakes. A temporary oil well-drilling platform, WODECO VI, drilled two exploratory holes near the south edge of the Montalvo trend and was in the process of drilling a third hole when the swarm commenced. The drilling was not interrupted; the hole was dry and was capped. At least two more dry holes were drilled nearby and were capped after the swarm. Platform A, on which a well blew out on January 28 1969 resulting in a massive spill of crude oil and gas, was constructed on September 14 1968 after the earthquake swarm ceased, and drilling commenced in November 1968.

We are intrigued with the possibility that the earthquakes and the oil-well operations may be linked in a way similar to the Denver earthquakes and the disposal of waste waters at the Rocky Mountain Arsenal (Healy and others, 1968). However, much more data of the kind presented by McCulloh (1969) bearing on the operations of the petroleum companies, such as production rates, volumes of fluids withdrawn and reinjected, down-hole pressure gradients and fluid pressure history, will be required for a more comprehensive study. On the basis of our cursory study of the limited available data, we conclude that there is no compelling evidence indicating that the earthquake swarm is related to oil-well drilling and exploration operations in the channel, because earthquake swarms appear to have occurred several times prior to oil exploration in the channel and do not constitute, therefore, a unique event in this region.

Miscellaneous Observations

Several Santa Barbara residents reported feeling a long-period ground motion similar to the gentle rocking of a ship on a calm sea. According to one observer, the motion was strongest between felt shocks, ceasing for a short time just before each recorded shock. Although some residents claimed to have been nearly nauseated, we were neither able to document the motion instrumentally nor experience it personally in their company. We interpret their sensations to be a psychological effect similar to the "sea-leg" effect.

Conclusions

The many minor earthquakes that took place in the Santa Barbara Channel during summer 1968 comprised an earthquake swarm. The swarm, which occurred in a nonvolcanic area, was characterized by the occurrence of numerous minor shocks not dominated by a single principal shock. Interpretations of the hypocentral data are not conclusive because the crustal velocities have not yet been determined in the channel region. Focal mechanism solutions are neither geometrically nor kinematically consistent with available geological data on shallow faults (<5 km) that have been mapped in the channel and onshore terranes. We postulate that the current activity is occurring on northwest-striking faults that are new, or previously unrecognized, or that are deeper and associated with a major northwest-trending gravity and magnetic anomaly. Cursory investigation of limited data on offshore oil-well platform operations reveal no compelling evidence relating the occurrence of the swarm to the withdrawal of, or exploration for, hydrocarbons. There is historic evidence, in fact, that earthquake swarms have occurred previously in the channel and thus constitute an integral characteristic of the seismicity of the Santa Barbara Channel.

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DEPARTMENT OF GEOLOGICAL SCIENCES
UNIVERSITY OF CALIFORNIA
SANTA BARBARA, CALIFORNIA (A.G.S.)

SEISMOLOGICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA (S.W.S., C.H.S.)

MARINE SCIENCE INSTITUTE
CONTRIBUTION NO. 1

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