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RECENT EARTHQUAKE ACTIVITY IN THE SANTA BARBARA CHANNEL REGION*

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ABSTRACT

A new network of seismograph stations surrounding the Santa Barbara Channel was established by the U.S. Geological Survey in late 1969. During the first 2 years of operation, 107 earthquakes were located in the region. The distribution of earthquake epicenters shows an east-west trending pattern that seems to be spatially related to offshore faults inferred from acoustic profiling. A composite first-motion plot from a cluster of ten earthquakes in the eastern channel suggests left-lateral strike-slip movements along a steeply dipping fault plane.

INTRODUCTION

The Santa Barbara Channel region forms the westernmost part of the Transverse Ranges province of California (Figure 1). It is one of the most seismically active areas in the State and has experienced two earthquakes of magnitude 6 or larger since 1900. Since 1932, instrumentally recorded earthquakes throughout southern California have been reported by the Seismological Laboratory of the California Institute of Technology. Allen *et al.* (1965) synthesized these earthquake data for the period from 1934 to 1963 and related them to the regional geological structures. Through the courtesy of Caltech, we obtained a copy of the magnetic tape containing their earthquake catalog for southern California from 1932 to 1971. Earthquake epicenters in the Santa Barbara Channel region as determined by Caltech are concentrated in the eastern part of the channel and are not obviously related to the mapped faults (Figure 2). Unfortunately, the distribution of Caltech's seismograph stations is not favorable for precise location of earthquakes in the Santa Barbara Channel. Sylvester *et al.* (1970) discussed the Caltech results for the earthquake swarm that occurred in the channel during the period from June 26 to August 3, 1968 but were unable to associate the swarm with any known fault.

A report on the geology, petroleum development, and seismicity of the Santa Barbara Channel region was prepared by the U.S. Geological Survey (USGS) (Vedder *et al.*, 1969a) subsequent to an offshore oil-well blowout that drew national attention. In that report, Hamilton *et al.* (1969) reviewed the seismicity and its possible associated effects in the region and noted that the limitations of the existing seismic network precluded identification of individual active faults within the channel.

In order to improve earthquake monitoring, a new network of seismograph stations surrounding the Santa Barbara Channel was established by the U.S. Geological Survey in late 1969 (Figure 1). In this paper, we report earthquakes located by this network for the period from January 1, 1970 to December 31, 1971 and show that the recent seismicity appears to be spatially related to recognized faults in the region.

GEOLOGICAL SETTING

The Santa Barbara Channel forms part of the westernmost segment of the Transverse Ranges province, in which west-trending geomorphic and structural features transect the

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northwest-trending grain that is characteristic of the remainder of southern California. The channel is nearly 120 km long and about 50 km wide north of Santa Rosa Island; and the deepest part, about midway between Capitan and Santa Rosa Island, is approximately 625 m below sea level. It is bordered on the north by the Santa Ynez Mountains and on the south by the northern Channel Islands. Point Conception and the west shelf of

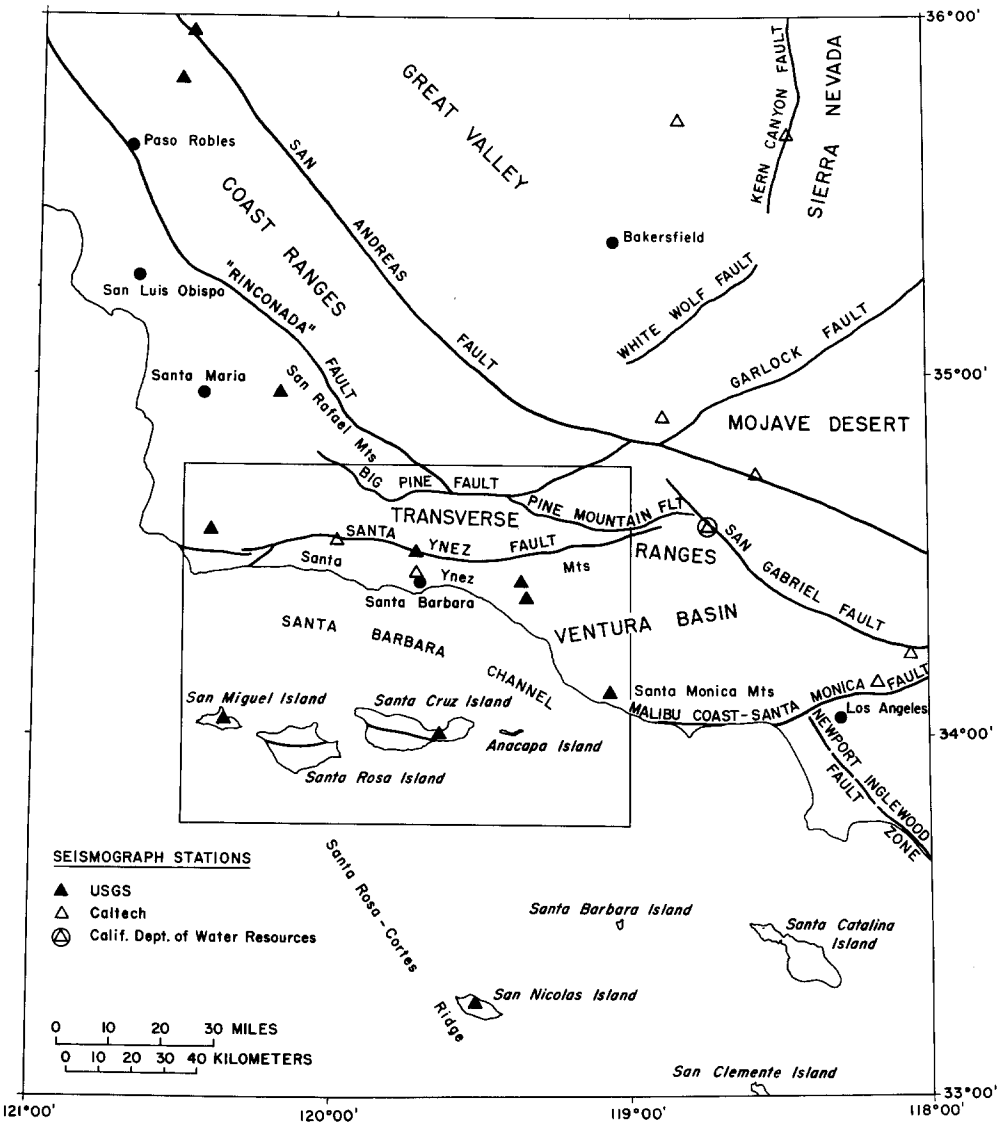

FIG. 1. Index map showing location of seismograph stations, selected major faults, and geomorphic provinces with respect to the Santa Barbara Channel region (boxed area).

San Miguel Island define the west end of the channel, but the structural basin beneath it may extend as far west as the continental slope. Hueneme Canyon and the shelf edge northeast of Anacapa Island lie at the east end of the channel. A generalized geological map of the Santa Barbara Channel region is shown in Figure 3.

The Santa Barbara Channel region is the western extension of the Ventura Basin, a late Cenozoic structural and depositional depression that contains more than 15,000 m of Cretaceous, Tertiary, and Quaternary strata. The mountain ranges and islands that bound

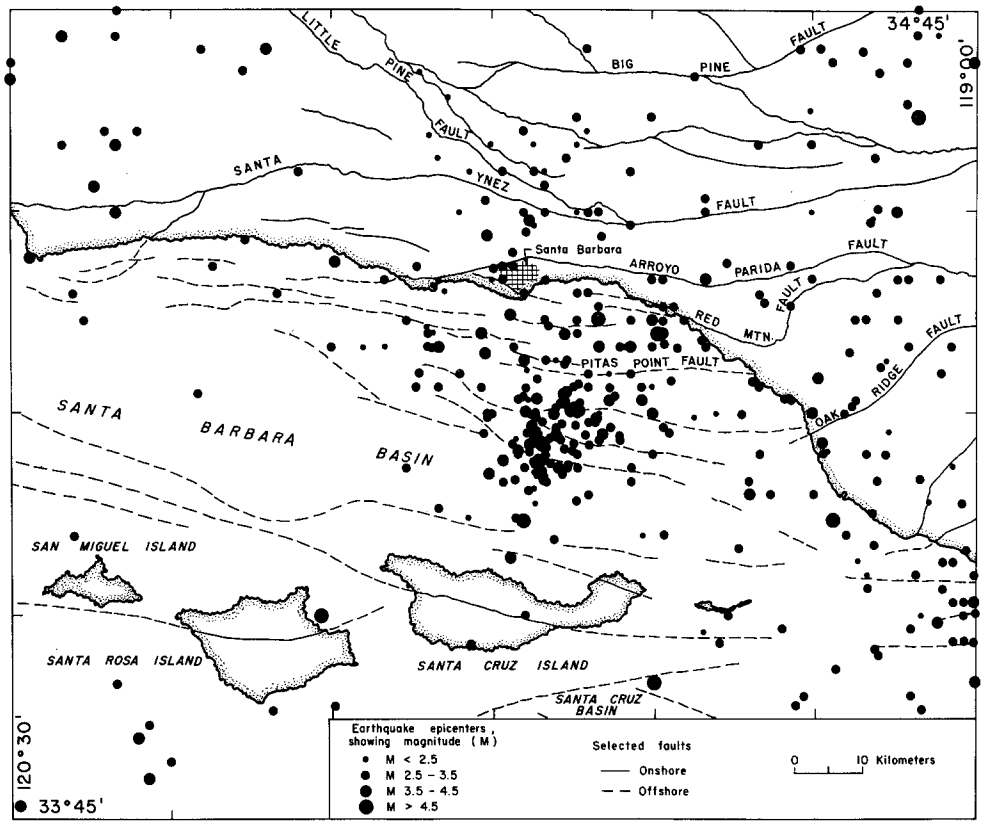

FIG. 2. Earthquake epicenters in the Santa Barbara Channel region from 1932 to 1971 as determined by the Seismological Laboratory of the California Institute of Technology. Offshore faults inferred chiefly from acoustic profiles.

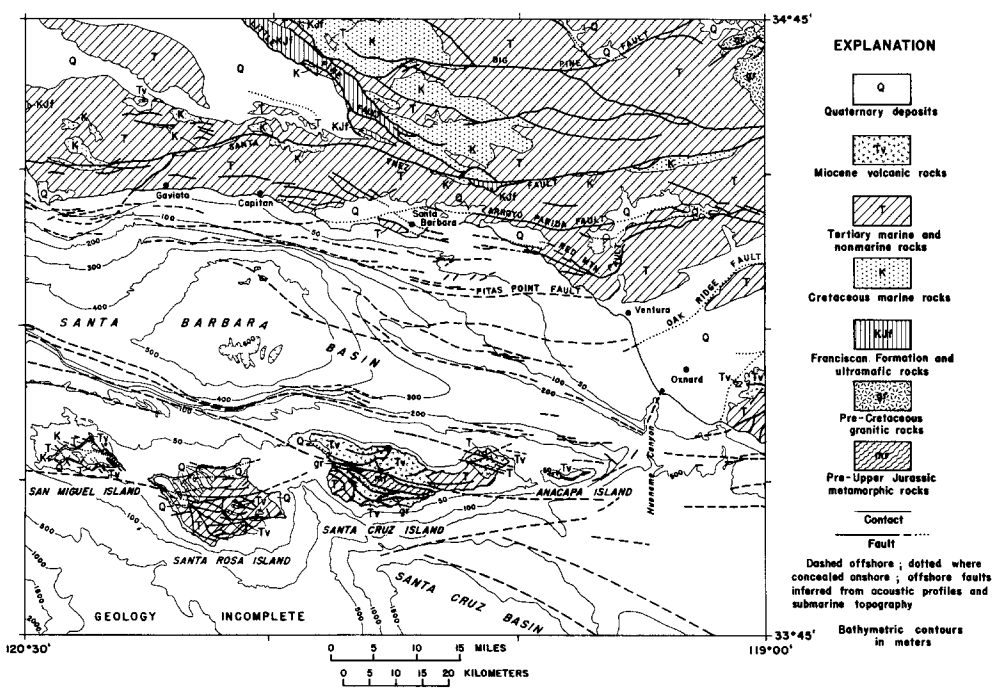

FIG. 3. Generalized geological map of the Santa Barbara Channel region. Modified from Jennings (1959), Vedder *et al.* (1969a), Weaver *et al.* (1969), Jennings and Strand (1969), Curran *et al.* (1971) Ziony *et al.* (1973), and unpublished maps of S. C. Wolf, H. G. Greene, and H. S. Wagner.

the channel on the north and south consist of complexly folded and faulted sedimentary, igneous, and metamorphic rocks. The enormously thick stratal sequences unconformably overlie, or are faulted against, so-called basement rocks that are chiefly pre-Cretaceous in age. In the Santa Ynez Mountains and San Rafael Mountains, these basement rocks include discontinuous, sheared masses of graywacke, shale, and chert that are intruded by ultramafic rocks. The sheared sedimentary rocks are commonly assigned to the Franciscan Formation. North and east of the Pine Mountain Fault, the basement rocks are composed mainly of Precambrian gneiss and Mesozoic granite. On Santa Cruz Island, schistose metamorphic rocks are intruded by hornblende diorite of Late Jurassic age; the subsurface boundary between these rocks and the Franciscan-like rocks in the Santa Ynez Mountains is uncertain. Vedder *et al.* (1969b) have summarized the stratigraphy of the overlying rock units, which range in age from Early Cretaceous to Holocene. In brief, this thick sequence consists of clastic sedimentary strata that are chiefly of marine origin and that are typified by lateral facies changes, particularly in the younger part. Miocene volcanic rocks locally intrude and commonly are interlayered with the clastic rocks on the islands and in the Santa Monica Mountains.

Structurally, the Santa Barbara Channel is a tectonic trough that is bounded on the north by a regionally extensive warped homocline in the Santa Ynez Mountains and on the south by the faulted insular platform of the northern Channel Islands. Although basement rocks have not been reached by wells in the deep part of the depression, where there may be as much as 15,000 m of sedimentary section, the total structural relief throughout the region probably is in excess of 18,300 m. This structural basin probably began to develop its present configuration near the close of Miocene time. Recurrent, nearly continuous tectonism has superimposed numerous faults and folds on the region since the beginning of the well-documented sedimentary record in Late Cretaceous time. The most severe episode of deformation may have transpired in Pleistocene time, during which several large folds were formed, many faults were active, and sedimentation rates were high (Vedder *et al.*, 1969a: Hamilton *et al.*, 1969).

North of the channel, two of the persistent structural features within the area of Figure 3 are the Big Pine and Santa Ynez faults. Left-lateral strike-slip movement is attributed to both, but displacements probably have been more complex. Reverse slip with a significant component of oblique movement almost certainly has taken place along the north-dipping western part of the Big Pine Fault (Vedder *et al.*, 1967), but approximately 16 km of left-lateral strike-slip movement is demonstrable farther east where the fault is nearly vertical (Hill and Dibblee, 1963; Vedder and Brown, 1968). At most places the Santa Ynez Fault dips steeply to the south, but the amount of net slip has not been determined; apparently the south side has been raised 1,500 to 3,000 m relative to the north side. A component of oblique slip also has been postulated for the Santa Ynez Fault (Page *et al.*, 1951). Both faults show geological evidence of Quaternary activity, for the Santa Ynez locally deflects stream courses (Page *et al.*, 1951) and displaces strata as young as late Pleistocene along its south branch (Ziony *et al.*, 1973), and the Big Pine seems to have displaced drainages and terrace surfaces (Hill and Dibblee, 1953; Vedder and Brown, 1968).

The mainland margin of the coastal area is dissected by many faults that cut late Quaternary strata and that generally are oriented east-west; the largest of these are the Arroyo Parida and Red Mountain faults. Most of these range-front faults exhibit reverse separation relations, and the Red Mountain Fault locally offsets Holocene deposits (Ziony *et al.*, 1973) and is associated with historic elevation changes (Buchanan *et al.*, 1973). Asymmetric folds, at places arranged *en echelon*, are aligned parallel to the trend of the channel and suggest southward-directed compressional stresses that have been active into late Quaternary time (Vedder *et al.*, 1969a).

Large west-trending fault zones, inferred from acoustic profiling, separate the eastern part of the channel floor into subparallel segments. The nature of movement and the dip of the fault planes within these zones are not definitely known. Along the south edge of the deep part of the channel, a zone of inferred faults closely follows the 200-m isobath. Within this zone, most of the faults apparently are nearly vertical or dip steeply to the south, but the kinds and amounts of displacement are conjectural. A similar but less well-defined set of inferred faults parallels the 200-m isobath along the north side of the central trough, suggesting that an elongate, downdropped block underlies the axial part of the channel. The western part of the channel is not well-known, but there the inferred structures seem to have the prevailing east-west trend, at least as far as Point Conception, where the pattern seems to change to a northwest-trending system. The Channel Islands are cut by west- to northwest-trending faults and folds that are superimposed on a structural block that may have remained elevated since early Pliocene time. Santa Rosa and Santa Cruz Islands are transected by large median faults that exhibit left-lateral offsets of stream courses. To the south of Anacapa and Santa Cruz Islands, a hypothetical fault that may be the westward continuation of the Santa Monica-Malibu Coast fault system can be extended at least to the Santa Rosa-Cortes Ridge on the basis of submarine topography, but there the offshore geology is not known well enough to project structures with confidence.

Some of the inferred faults in the northeastern part of the channel seem to displace the sea floor (Hamilton *et al.*, 1969), but those that lie along the north edge of the island platform are buried by strata that may be as old as Pliocene. Landward tilting of Pleistocene terraces on the northeast side of Santa Cruz Island and on Ancapa Island (Weaver *et al.*, 1969) may imply Quaternary uplift on faults south of the site of the terraces, and offset drainages in alluvial deposits along the median faults on Santa Rosa and Santa Cruz islands indicate probable latest Pleistocene or younger movement.

Seismograph Stations

The Santa Barbara Channel network of seismograph stations operated by the U.S. Geological Survey consists of eight telemetered stations: SBCC (San Rafael Mountains), SBLP (near Lompoc), SBLC (near Santa Barbara), SBCL (near Ojai, later moved and renamed SBCD), SBLG (near Laguna Point), SBSM (San Miguel Island), SBSC (Santa Cruz Island), and SBSN (San Nicolas Island). Station data including coordinates and elevations are given in Table 1, and station locations with respect to geographical and structural features are shown in Figure 1.

The equipment at each station includes a vertical-component 1-Hz seismometer, a package containing a preamplifier and voltage-controlled oscillator, and batteries. The frequency-modulated tone produced at each station is carried by wire (or radio from offshore stations) to a terminal where it is combined with tones from the other stations. The resulting multiplexed signal is then transmitted by a voice-grade telephone circuit to Menlo Park, California. There, the eight channels of data on the telephone line are separated, demodulated, and recorded on a 16-mm film recorder (Develocorder). In addition, two timing signals (WWVB on two traces, and a chronometer) are recorded simultaneously with the seismic signals. Magnification for individual stations is adjusted according to the background noise level in steps of 6 db. Most of the Santa Barbara network stations are operated at magnification of about 100,000 at 1 Hz.

In locating earthquakes in the Santa Barbara Channel region, we have supplemented our readings with those from stations operated by the Seismological Laboratory, California Institute of Technology, and the California Department of Water Resources.

TABLE 1

STATION DATA

Station Code	Latitude (N)	Longitude (W)	Elevation (m)	Station Correction (sec)
A. Stations operated by U.S. Geological Survey				
SBCC	34° 56.48′	120° 10.32′	610	0.18
SBCD	34° 22.12′	119° 20.63′	213	0.02
SBCL	34° 24.75′	119° 21.67′	177	0.02
SBLC	34° 29.79′	119° 42.81′	1190	−0.02
SBLG	34° 6.57′	119° 3.85′	415	−0.17
SBLP	34° 33.62′	120° 24.03′	134	−0.08
SBSC	33° 59.68′	119° 37.99′	457	0.08
SBSM	34° 2.25′	120° 20.99′	172	−0.04
SBSN	33° 14.70′	119° 30.40′	259	−0.14
JOL	36° 5.02′	121° 10.15°	336	−0.17
PNC	36° 33.73′	121° 38.18′	305	−0.42
SHG	36° 24.83′	121° 15.22′	192	−0.46
TAY	35° 56.73′	120° 28.45′	552	−0.13
WKR	35° 48.87′	120° 30.67′	503	−0.07
B. Stations operated by California Institute of Technology				
FTC	34° 52.40′	118° 53.60′	990	−0.26
ISA	35° 39.80′	118° 28.40′	835	0.20
MWC	34° 13.40′	118° 3.50′	1730	0.24
PAS	34° 8.90′	118° 10.30′	295	−0.02
SBC	34° 26.50′	119° 42.80′	90	0.02
SYP	34° 31.60′	119° 58.70′	1305	0.02
SWM	34° 43.10′	118° 34.90′	1220	0.01
WDY	35° 42.00′	118° 50.60′	500	0.15
C. Stations operated by California Department of Water Resources				
CSP	34° 17.88′	117° 21.45′	1268	0.28
PEC	33° 53.52′	117° 9.64′	616	0.19
PYR	34° 34.08′	118° 44.46′	1247	0.15

Additional readings from some of our central California network stations are included. All stations used are listed in Table 1.

DATA PROCESSING AND ANALYSIS

The telemetered seismic data recorded on 16-mm film are treated manually to provide information on first *P* arrivals, first motions, and signal durations. These data are then processed by computer to give origin time, hypocenter location, magnitude, and fault-plane solution of the earthquakes. Earthquakes are located mainly on the basis of *P* arrival times from seismograph stations with clear first *P* arrivals. *S* arrivals are used to supplement the *P* arrivals whenever possible. The HYPO71 computer program (Lee and Lahr, 1972) is used to locate hypocenters, compute magnitudes, and plot first-motion patterns. This program employs Geiger's (1912) method to determine hypocenters by minimizing the residuals between observed and calculated arrivals. Travel times from a trial hypocenter to the stations and their partial derivatives are computed on the assumption of a horizontal multilayer model by a technique introduced by Eaton (1969).

There are no published descriptions of the configuration and nature of the crust beneath the Santa Barbara Channel as determined by explosions. Shor and Raitt (1958) interpreted the crustal structure of part of the continental borderland of southern California by seismic refraction methods, but their seismic profiles are south of the Santa Barbara Channel. Although Healy (1963) reported several crustal models that are consistent with data obtained from two reversed seismic-refraction profiles between San Francisco and Los Angeles, his profiles transect only the northeasternmost part of the region covered in this report.

We have adopted the four-layer model of Healy (1963, p. 5783) as an approximation to the crustal structure beneath the channel. This model is specified by

Layer	Depth (km)	*P* Velocity (km/sec)
1	0. to 2.6	3.0
2	2.6 to 16.7	6.1
3	16.7 to 26.1	7.0
4	below 26.1	8.1

We further assume that the ratio of *P* velocity to *S* velocity is constant and has a value 1.78. Average station *P* residuals from 95 selected events are used as station corrections in relocating all 107 earthquakes; their values are included in Table 1.

The method used for estimating the earthquake magnitude follows that of Lee *et al.* (1972), in which the magnitude is based on the average magnitudes estimated at various stations. Station magnitude (M) is derived from its recorded signal duration (τ) according to

$$M = -0.87 + 2.00 \log(\tau) + 0.0035\,\Delta$$

where Δ is the epicentral distance in kilometers. The signal duration is defined as the duration time in seconds from the onset of the first *P* arrival to the point where the trace amplitude (peak to peak) falls below 1 cm as it appears on the Geotech film viewer ($\times 20$ magnification).

Earthquake Hypocenters and Their Accuracy

Results of the monitoring of 107 earthquakes that occurred in the Santa Barbara Channel region during 1970 and 1971 are given chronologically in Table 2. Included are the origin time, location of hypocenter (epicenter and focal depth), magnitude, and number of stations used. In addition, five parameters are listed as a means of evaluating the quality of hypocenter solution. These parameters are: (1) the largest azimuthal separation between stations (α), (2) epicentral distance to the nearest station (β), (3) root-mean-square error of the time residuals (γ), (4) standard error of the epicenter (ε_1), and (5) standard error of the focal depth (ε_2). On the basis of these parameters, the general reliability of each earthquake solution is graded as either excellent (A), good (B), fair (C), or poor (D). Exact rules of quality classification are given in the footnote to Table 2.

A brief discussion of the accuracy of hypocenter solution of earthquakes has been given by Lee *et al.* (1971). To obtain a reliable epicenter, α should be less than 180°; to obtain a reliable focal depth, β should be less than the focal depth. In addition, systematic errors arise from uncertainties in the crustal velocity model. These errors cannot be determined without controlled experiments, such as calibrated explosions in the focal region. Because all hypocenter solutions for earthquakes are provided, their quality varies. Although standard errors of epicenter and focal depth (ε_1 and ε_2) are given, they must be interpreted with caution, especially for quality C and D solutions. Hypocenter solutions for known blasts distributed throughout the San Francisco Bay region indicate

TABLE 2A. LIST OF EARTHQUAKES IN THE SANTA BARBARA CHANNEL REGION (1970)*

	1970	HR	MN	SEC	LAT N	LONG W	DEPTH	MAG	NO	GAP	DMIN	RMS	ERH	ERZ	Q
**	JAN 2	10	45	21.5	34-17.1	119-38.5	5.0	3.5	11	151	18.5	0.39	2.2	2.6	C
	2	19	57	47.7	34-18.4	119-42.9	5.0	2.6	8	177	15.0	0.19	2.6	2.6	C
	8	5	17	42.9	34-29.9	119-18.8	5.0	2.4	7	188	36.7	0.20	3.9	3.6	D
**	10	2	47	2.8	34-24.6	119- 8.0	13.4	3.0	17	142	40.0	0.31	1.4	1.1	C
	14	17	17	4.3	34-23.4	119-52.3	1.2	2.1	7	178	18.1	0.10	0.9	0.8	B
	29	15	32	59.4	34-25.3	119-55.6	13.2	2.0	6	155	12.6	0.10	1.0	1.1	C
	FEB 14	12	56	24.7	34-14.4	119-40.8	5.0	2.5	7	79	27.6	0.18	1.4		C
	20	7	35	35.2	34-23.4	119-46.2	12.4	2.4	8	118	7.7	0.08	0.8	0.6	B
	MAR 4	17	24	57.5	34-22.4	120- 7.9	5.0	1.9	6	122	32.2	0.27	2.7		C
	7	3	56	49.6	33-53.2	120- 1.4	3.6	1.9	6	228	34.5	0.05	1.7	0.7	C
	13	20	40	9.7	34-23.7	119-34.3	11.7	1.8	6	133	17.2	0.08	0.8	1.1	B
	20	12	48	43.8	34-21.3	120-24.1	5.0	1.9	6	188	22.8	0.23	3.5		D
	20	13	18	36.8	34-21.3	120-24.1	5.0	2.0	6	188	22.7	0.17	2.7		D
	23	13	16	9.2	34- 0.3	119- 6.4	4.2	1.9	6	189	12.3	0.02	0.3	0.3	C
**	26	22	0	20.6	34-15.7	119-36.4	5.0	2.6	12	89	22.2	0.24	1.4	2.3	C
	29	16	7	17.9	34-15.4	119-38.2	9.1	1.7	6	122	27.5	0.06	0.8	1.6	B
**	31	11	1	51.4	34-15.4	119-34.8	5.0	2.7	12	80	23.8	0.17	0.9	1.6	C
	APR 6	23	3	50.4	34-22.4	119-35.9	5.0	2.1	7	113	13.0	0.36	3.0		C
	15	23	32	4.0	34-22.3	120-24.1	5.0	1.9	6	188	21.0	0.24	2.8		D
**	16	21	55	48.5	34-15.6	119-42.9	9.9	2.9	14	77	20.2	0.13	0.6	0.7	B
	19	7	11	58.4	34-28.7	119-49.3	1.1	2.1	6	112	10.1	0.19	2.1		C
	22	2	43	29.9	34-31.2	119-25.3	4.1	2.1	7	141	26.9	0.29	1.6	12.6	C
**	23	10	42	53.3	34-26.4	119-23.9	5.0	2.5	14	103	29.0	0.34	1.6	2.0	C
	30	3	59	42.8	34-14.0	119-34.1	5.0	2.7	10	88	26.7	0.10	0.6	1.1	B
	MAY 2	1	52	3.3	34-14.9	119-33.7	8.4	2.3	9	92	29.0	0.16	0.9	1.5	C
	2	15	43	39.5	34-21.3	120-24.1	5.0	2.2	6	188	22.9	0.24	3.8		D
**	16	1	47	24.5	34-26.7	119-47.0	10.7	3.3	19	60	6.5	0.26	1.1	0.8	B
**	25	2	57	54.3	34-14.5	119-44.6	8.1	2.7	11	89	22.4	0.09	0.6	0.6	B
	25	9	12	52.8	34-14.0	119-45.4	5.0	1.8	8	147	23.4	0.15	1.2		C
	JUN 11	1	12	59.6	34-20.3	120- 2.6	0.8	2.7	6	151	21.7	0.28	2.8		C
	20	14	2	29.5	34-41.3	119-30.3	5.0	2.1	8	166	28.6	0.32	2.1	7.0	C
	20	15	23	16.4	33-46.2	120- 3.6	5.0	2.4	6	179	40.0	0.12	0.9	1.4	B
**	20	15	27	31.2	33-46.2	120- 4.1	5.0	3.0	8	181	39.6	0.09	0.8	2.0	C
	JUL 4	10	9	35.1	34-42.7	119-31.5	5.0	2.5	9	96	29.5	0.18	1.2	2.0	C
	24	11	55	27.1	34- 1.1	119- 9.1	3.6	2.5	9	163	12.9	0.05	0.3	0.5	B
**	29	21	13	18.2	34-34.7	119-49.8	5.0	2.3	12	84	14.0	0.40	2.1	3.2	C
**	AUG 26	1	8	59.7	34-18.1	119-14.3	7.9	3.6	18	69	16.8	0.40	1.5	1.8	C
	29	8	14	16.9	34-15.0	119-42.2	5.0	2.2	8	107	21.3	0.13	1.0	15.0	C
**	SEP 7	9	35	56.4	34-29.9	119-45.3	1.2	2.7	10	128	3.9	0.27	1.9	1.1	B
**	12	19	17	32.2	34-26.4	119-25.6	5.0	3.2	6	193	6.7	0.31	4.8	4.8	D
	12	20	52	14.0	34-15.2	119-38.3	5.0	1.3	6	124	27.9	0.16	1.7		C
	OCT 6	8	0	46.9	34-17.1	119-41.8	9.7	1.6	7	126	23.6	0.21	1.0	1.7	C
**	17	20	17	5.2	34-35.6	119-50.2	2.0	2.5	11	203	14.9	0.12	0.5	0.4	C
	NOV 7	15	54	31.3	34-25.5	119-26.8	5.0	2.4	6	148	8.0	0.26	3.5	5.8	C
	8	8	27	9.0	33-52.4	120-15.5	5.0	2.4	7	200	20.1	0.15	2.1	2.6	C
	NOV 15	5	10	5.0	34-29.7	119-39.1	24.0	1.9	4	193	5.7	0.01			C
	22	12	0	32.0	34- 8.4	119- 2.3	11.5	1.9	5	187	4.1	0.06	1.3	1.2	C
	DEC 6	1	19	33.5	34-23.5	119-50.9	17.9	2.1	6	203	13.5	0.05	1.2	1.0	C
**	9	13	3	56.2	34-24.9	119- 8.4	6.0	2.7	7	104	20.4	0.10	1.0	1.3	B
	30	9	50	6.8	34-17.5	119-45.8	5.0	2.0	8	135	17.3	0.17	1.2	14.3	C
	31	23	5	11.5	34-42.5	120-17.3	7.9	3.2	8	120	19.3	0.24	1.8	2.2	C

TABLE 2B. LIST OF EARTHQUAKES IN THE SANTA BARBARA CHANNEL REGION (1971)*

	1971	HR	MN	SEC	LAT N	LONG W	DEPTH	MAG	NO	GAP	DMIN	RMS	ERH	ERZ	Q
**	JAN 1	20	36	20.4	34-19.0	119-20.9	2.0	3.1	8	85	10.8	0.38	2.3		C
	8	9	31	2.2	34- 2.6	119-40.6	17.6	1.9	9	99	6.7	0.30	1.7	2.0	B
	8	10	15	41.0	34- 1.8	119-40.8	18.0	1.4	7	139	5.7	0.24	2.2	3.4	C
	FEB 1	17	9	50.4	34-15.1	119- 8.7	2.3	2.5	8	108	17.5	0.10	0.7	0.8	B
	5	1	36	47.2	34-29.9	119-25.8	5.0	2.1	7	137	26.0	0.57	6.9		D
	MAR 5	14	29	59.0	33-49.0	120- 0.7	0.2	2.5	6	165	39.7	0.35	1.4	11.4	C
	16	13	22	43.7	34-14.4	119-42.9	1.0	2.1	6	135	28.2	0.14	1.2		C
	25	0	40	29.3	34-17.2	119-32.9	9.4	1.9	6	127	22.1	0.12	1.3	1.5	C
	APR 21	3	12	10.1	34- 9.8	119-38.1	13.7	1.9	7	123	18.6	0.13	1.3	1.1	B
	24	0	24	18.2	34-38.9	120-24.1	5.0	2.5	6	176	9.7	0.51	4.9	4.5	D
	27	6	55	59.9	33-45.6	120- 3.4	0.8	3.6	12	180	41.1	0.23	1.6	1.3	C
	27	7	4	17.5	33-45.5	120- 4.8	6.8	2.2	6	205	48.9	0.13	1.9	2.5	C
**	MAY 7	1	22	30.1	34-14.8	119-40.2	7.7	3.1	13	77	22.0	0.20	0.9	1.1	C
	7	1	23	37.6	34-15.6	119-41.4	11.1	2.4	6	109	26.2	0.07	0.6	0.8	B
	7	1	52	10.9	34-15.5	119-41.2	5.0	1.7	6	78	26.5	0.07	0.7	16.0	C
	7	2	3	21.9	34-15.1	119-40.4	9.6	2.6	8	77	27.4	0.24	1.6	2.2	C
	7	2	16	6.0	34-15.7	119-41.6	2.7	1.8	6	128	26.1	0.16	1.2		C
	7	4	40	12.6	34-15.5	119-41.1	2.6	1.6	8	111	26.6	0.09	0.6		C
	7	9	26	16.3	34-15.1	119-42.1	8.1	2.0	7	107	27.2	0.17	1.3	2.0	C
	7	11	6	52.3	34-15.2	119-41.4	7.3	1.9	7	110	27.1	0.11	0.8	3.0	C
**	7	18	33	14.6	34-17.1	119-38.9	5.0	2.3	8	76	18.4	0.28	1.8	3.4	C
**	7	18	36	43.6	34-15.2	119-40.7	7.8	2.3	10	77	21.1	0.19	1.1	1.9	C
	12	14	51	23.5	34-19.8	119-21.8	0.2	2.5	6	82	9.1	0.47	4.0		C
	15	15	21	58.4	34-15.2	119-41.1	5.0	1.9	7	103	27.1	0.13	1.0	18.7	C
**	15	16	54	14.1	34-26.6	119-47.1	10.5	2.7	12	81	6.6	0.20	1.0	1.0	B
	JUN 10	10	45	25.0	33-45.7	120- 8.2	5.0	1.9	6	193	36.4	0.26	2.5	8.3	D
	10	12	38	25.7	34-13.9	119-41.3	9.6	2.2	8	79	26.7	0.18	1.1	1.8	C
	18	15	30	30.8	33-53.7	119-40.1	11.1	1.6	6	116	11.5	0.07	1.1	1.4	B
	JUL 10	10	36	16.4	34-15.5	119-41.9	7.8	2.1	9	77	26.5	0.25	1.4	3.1	C
	10	14	52	36.7	34-15.7	119-42.4	5.0	1.8	7	130	26.1	0.07	0.6	9.8	C
**	13	13	10	26.8	33-50.5	120- 2.7	2.0	2.7	10	165	35.7	0.22	1.6	15.0	C
	19	16	31	49.9	33-45.9	120- 8.1	5.0	1.9	9	192	36.2	0.33	2.2	2.0	D
	AUG 12	11	38	24.3	34-14.9	119-37.6	9.9	2.2	6	115	28.2	0.15	1.5	1.6	C
	27	12	45	15.5	34-38.6	119-55.9	5.0	2.0	4	163	25.8	0.02			C
	29	17	25	21.8	34-34.6	120- 2.5	13.5	1.4	5	161	31.4	0.01	0.1	0.3	C
	30	1	49	37.8	33-53.1	119-22.5	5.0	1.5	6	141	26.8	0.12	1.2	12.5	C
	31	7	54	23.4	34- 0.4	120-14.7	5.0	1.9	7	198	10.3	0.11	1.1	1.9	C
**	SEP 13	1	3	3.5	34-14.9	119-41.6	9.6	2.8	13	78	21.4	0.20	1.0	1.2	C
**	13	1	12	27.2	34-15.1	119-41.5	5.0	2.6	12	77	21.2	0.19	1.0	1.5	C
	17	1	46	29.2	34-33.7	120-23.3	0.9	2.3	4	122	1.2	0.00			C
	17	9	19	5.0	34-17.4	119-43.3	8.4	2.4	6	95	22.9	0.08	0.8	1.8	B
	18	9	3	24.8	34-17.4	119-44.1	5.0	2.2	7	159	23.0	0.14	1.3	19.1	C
	22	0	25	35.1	34-15.6	119-40.9	5.0	2.2	7	77	26.3	0.17	1.3	19.8	C
	24	0	30	40.7	34-23.5	119-53.6	14.5	2.1	5	97	20.2	0.09	0.7	0.8	C
**	27	20	59	3.3	34-17.6	119-21.5	8.8	3.1	11	108	33.9	0.18	1.0	1.1	C
	OCT 4	7	53	51.2	34-18.0	119-45.8	5.0	2.5	8	73	22.3	0.17	1.0	5.4	C
	26	14	24	10.5	33-52.6	119-17.9	2.9	2.1	9	156	33.7	0.12	0.7	2.2	C
	28	16	17	58.1	34-15.4	119-41.9	0.4	2.8	5	171	26.7	0.16	3.2		D
**	29	3	47	9.3	34-15.3	119-38.8	5.0	2.9	12	80	21.6	0.21	1.0	1.7	C
	NOV 4	18	22	37.4	34-27.0	119-27.1	5.0	2.0	6	157	24.6	0.41	3.1		C
	DEC 14	21	21	11.9	34-22.8	119-18.8	7.1	1.9	9	139	3.1	0.16	0.9	1.1	C
	15	18	47	44.4	34-22.2	119-18.7	8.9	1.3	7	137	2.9	0.10	0.8	1.1	B
	19	2	13	36.3	34-23.1	119-19.5	9.0	2.4	9	121	2.6	0.13	0.8	0.7	B
	20	14	29	31.2	34-17.7	120-14.7	5.0	2.2	9	136	30.1	0.35	2.0	2.6	C
	30	19	17	54.1	34- 6.5	120- 6.8	5.0	2.2	8	144	23.1	0.42	2.8	4.1	C
	30	23	3	41.3	34-15.6	119-41.3	5.0	2.1	8	101	26.4	0.14	0.9	18.6	C

See footnotes for Table 2a and b on the following page.

that the true positions are within the standard error limits of the solutions, provided that (1) $\alpha < 180°$ and (2) β is not larger than a few kilometers. For example, comparison of locations determined for well-recorded quarry blasts (solution quality A) with the known coordinates indicates a typical error of about 1 km. As suggested by known blasts, a general statement on the accuracy of our hypocenter solutions is as follows

Solution Quality	Approximate accuracy	
	Epicenter (km)	Focal Depth (km)
A (excellent)	1	2
B (good)	2.5	5
C (fair)	5	>5
D (poor)	>5	>5

(*Footnotes to Table 2a and b.*)

* The following data are given for each event:

(1) Origin time in Greenwich Civil Time: date, hour (HR), minute (MN), and second (SEC). If ** precedes the date, it indicates that this event also appeared in the Caltech catalog.
(2) Epicenter in degrees and minutes of north latitude (LAT N) and west longitude (LONG W).
(3) DEPTH, depth of focus in kilometers.
(4) MAG, Richter magnitude of the earthquake.
(5) NO, number of stations used in locating earthquake.
(6) GAP, largest azimuthal separation in degrees between stations.
(7) DMIN, epicentral distance in kilometers to the nearest station.
(8) RMS, root-mean-square error of the time residuals: $RMS = [\Sigma_i(R_i^2/No)]^{\frac{1}{2}}$ where R_i is the observed seismic-wave arrival time minus the computed time at the ith station.
(9) ERH, standard error of the epicenter in kilometers: $ERH = [SDX^2 - SDY^2]^{\frac{1}{2}}$. SDX and SDY are the standard errors in latitude and longitude, respectively, of the epicenter. When $NO \leqq 4$, ERH cannot be computed and is left blank.
(10) ERZ, standard error of the focal depth in kilometers. When $NO \leqq 4$, ERZ cannot be computed and is left blank. If $ERZ \geqq 20$ km, it is also left blank.
(11) Q, solution quality of the hypocenter. This measure is intended to indicate the general reliability of each solution.

Q	*Epicenter*	*Focal Depth*
A	excellent	good
B	good	fair
C	fair	poor
D	poor	poor

Q is based on both the nature of the station distribution with respect to the earthquake and the statistical measure of the solution. These two factors are each rated independently according to the following schemes:

Station Distribution

Q	*NO*	*GAP*	*DMIN*
A	$\geqq 6$	$\leqq 90°$	$\leqq$ Depth or 5 km
B	$\geqq 6$	$\leqq 135°$	$\leqq 2 \times$ Depth or 10 km
C	$\geqq 6$	$\leqq 180°$	$\leqq 50$ km

Statistical Measures

Q	*RMS (sec)*	*ERH (km)*	*ERZ (km)*
A	< 0.15	< 1.0	< 2.0
B	< 0.30	< 2.5	< 5.0
C	< 0.50	< 5.0	
D	Others		

Q is taken as the average of the ratings from the two schemes, i.e., an A and a C yield a B, and two B's yield a B. When the two ratings are only one level apart the lower one is used, i.e., an A and a B yield a B.

Because we do not have calibrated explosions in the Santa Barbara Channel, it is difficult to ascertain the hypocenter accuracy of our earthquake solutions. Extrapolation from experience in central California suggests that earthquake locations in the channel are accurate to about 5 km in general. This conclusion is supported by the fact that we were able to locate several offshore blasts near Santa Cruz Island within 5 km of their given positions.

Caltech's earthquake catalog for southern California (1932–1971) lists 606 earthquakes in the Santa Barbara Channel region, and their epicenters are shown in Figure 2. A frequency-magnitude plot for the 40 years of Caltech data is diagrammed in Figure 4. For the period from 1970 to 1971, the Caltech catalog shows 25 earthquakes in the channel region; and, during the same period, we have located 107 earthquakes. It is interesting to note on Figure 4 that the *b*-slope values of these two sets of data are almost identical (1.05 versus 1.03), and that the different "*a*" values result from the different lengths of

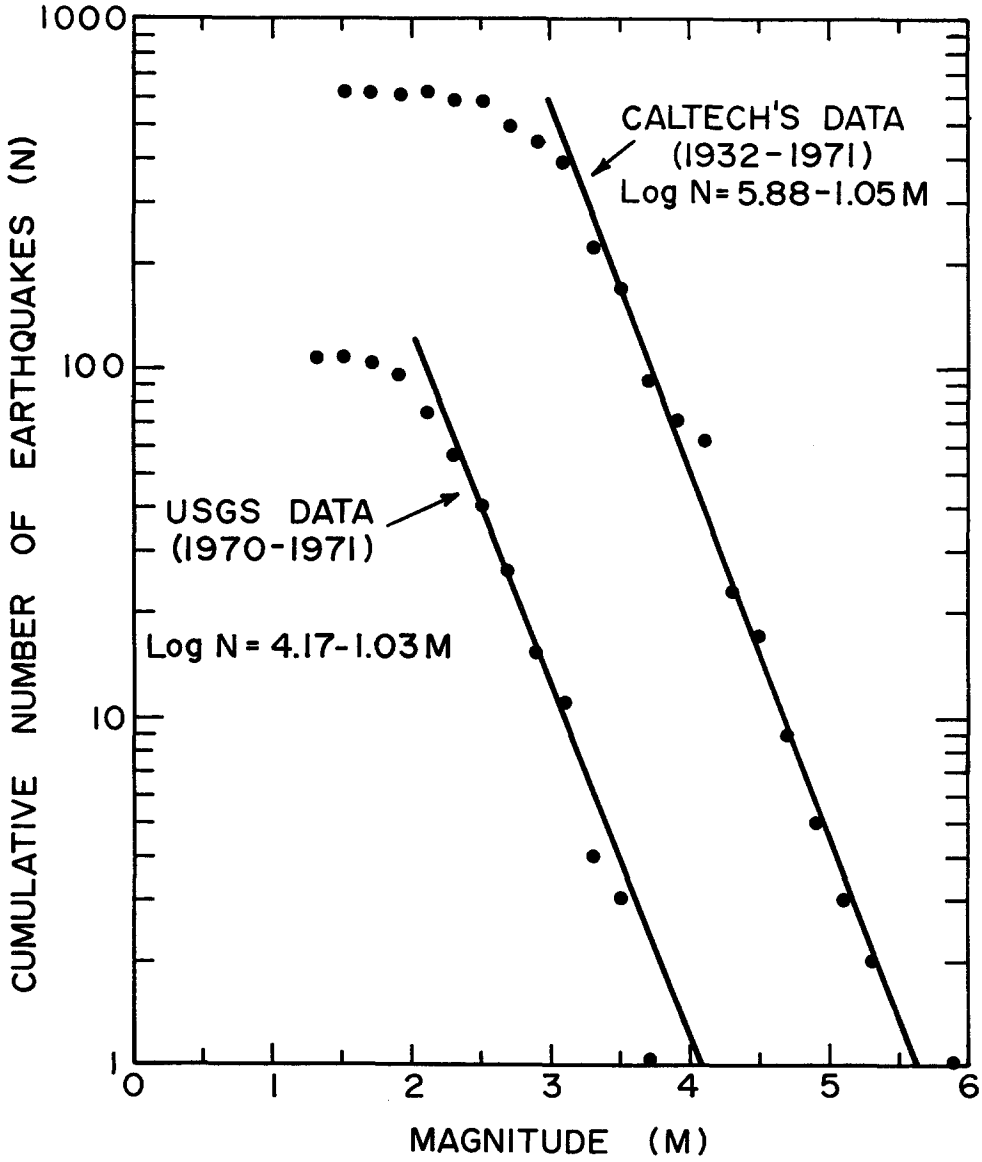

FIG. 4. Frequency-magnitude plot of Caltech data (1932–71) and USGS data (1970–71).

time represented (2 versus 40 years). The Caltech data are better for estimating the recurrence frequency of larger earthquakes because they covered a much longer time interval. Based on Caltech's results, it is reasonable to expect one earthquake with magnitude greater than 5 to occur in the Santa Barbara Channel region over a period of 10 years.

As the 25 events in the Caltech catalog were included in the USGS study, we can compare the hypocenter solutions given by the two networks. Figure 5 shows a plot of magnitude determined by the USGS versus that determined by Caltech. If both determinations were identical, all points would fall on the diagonal line. There are some points scattered about this line, but for most earthquakes, the magnitude determined by USGS agrees well (within $\frac{1}{4}$ unit) with that determined by Caltech. The plotted points suggest that the USGS magnitude may be systematically lower than the Caltech magnitude by 0.1 unit.

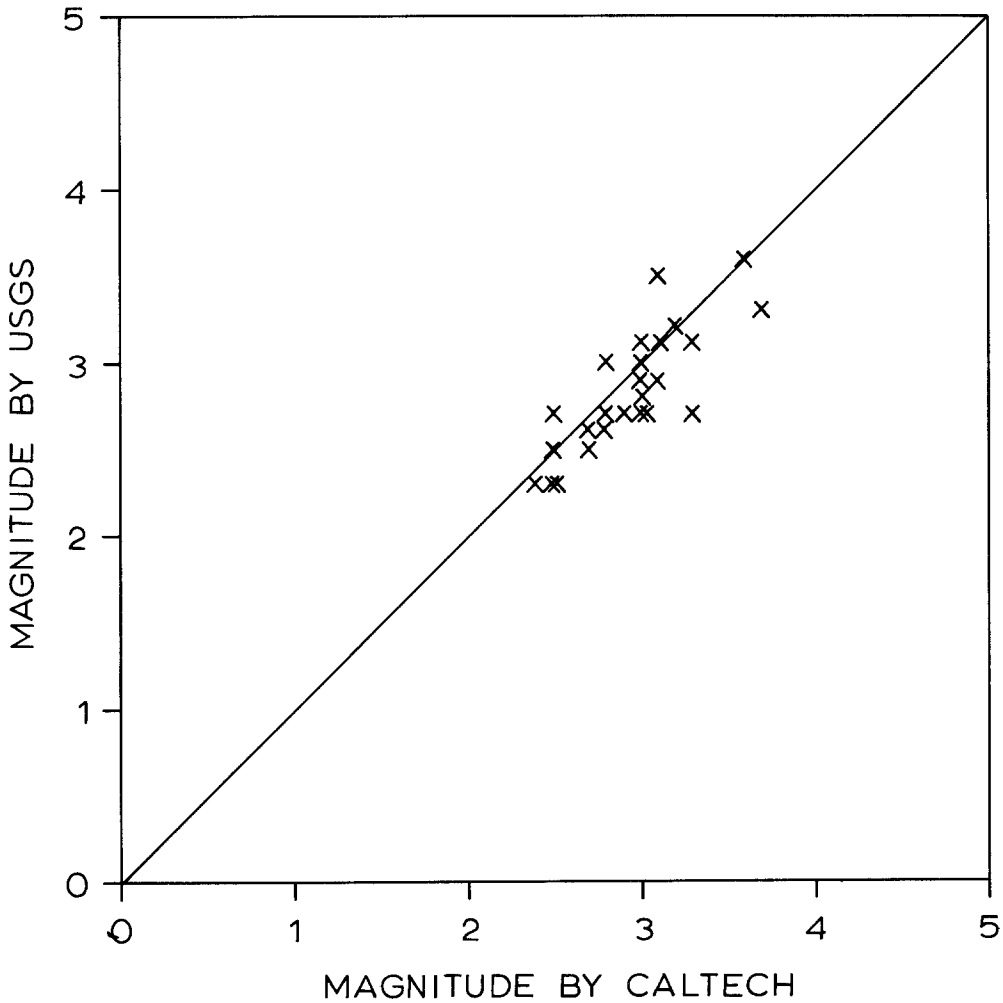

FIG. 5 USGS magnitude versus Caltech magnitude for 25 earthquakes listed in Caltech catalog (1970–71).

In Figure 6, the epicenters for the 25 events determined by Caltech are compared with those determined by USGS. Along the coast of Santa Barbara and Ventura, epicenter solutions given by both groups are similar. In the eastern part of the Santa Barbara Channel, the USGS solutions indicate that earthquakes occurred along a well defined zone that is spatially associated with offshore faults inferred from acoustic profiling,

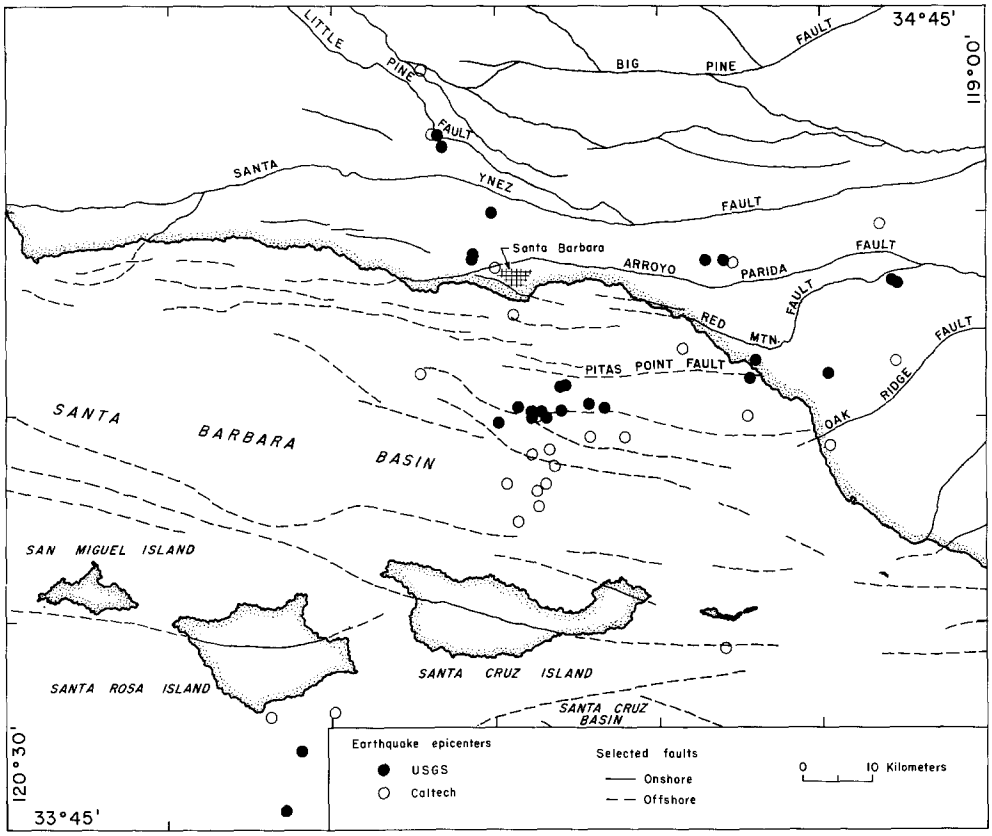

FIG. 6. Comparison of epicenters determined by U.S. Geological Survey (dots), and epicenters determined by Caltech (circles) for the same 25 earthquakes in 1970–71.

whereas the Caltech solutions suggest a scatter between Santa Barbara and Santa Cruz Island.

EARTHQUAKE EPICENTERS, FOCAL DEPTHS AND FOCAL MECHANISMS

The earthquake epicenters in Table 2 were plotted using the ranges of magnitude shown in Figure 7. In the eastern part of the Santa Barbara Channel, there is a concentration of epicenters; elsewhere the distribution of epicenters is scattered. Seismicity in the northern Santa Barbara Channel region presumably is related to several major fault zones. Along the coast, some earthquakes may be associated with the system of faults that includes the Red Mountain and Arroyo Parida faults. Farther north, a few epicenters fall near the surface traces of the Santa Ynez, Little Pine, and Big Pine faults.

A concentration of 1970 and 1971 epicenters forms an east-trending linear pattern about 25 km long and less than 5 km wide along an inferred offshore fault that extends seaward from near the probable western termination of the Oak Ridge Fault (Figure 3). Inactivity along the nearshore part of this submarine zone during the 2-year period suggests that there is no juncture between it and the inferred location of the Oak Ridge Fault on land. Moreover, in the nearshore area, faults are not evident in the younger sea-floor sediment examined by means of acoustic reflection surveys. Therefore, the Oak Ridge Fault probably is a distinct and separate feature along which the current state of activity is unknown, and the inferred offshore fault may be an *en echelon* break. Farther north, another set of epicenters seems to form a similar east-west linear pattern along the Pitas Point Fault.

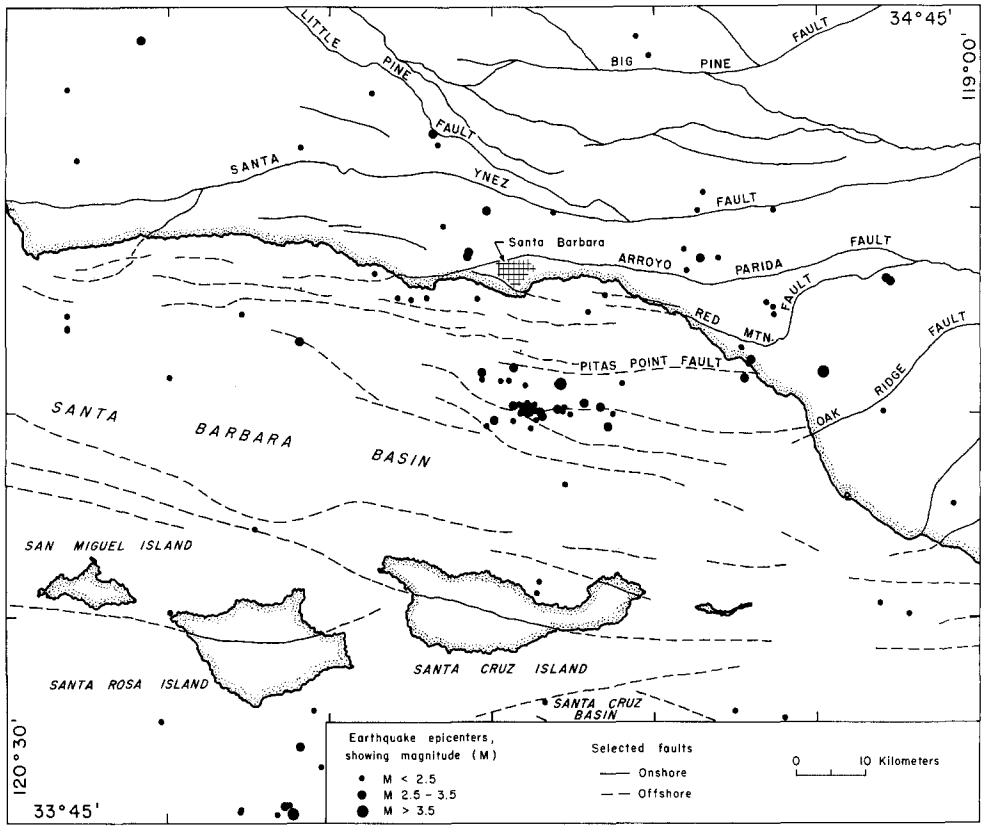

FIG. 7. Earthquake epicenters in the Santa Barbara Channel region from 1970 to 1971 as determined by the U.S. Geological Survey.

Fewer earthquakes were recorded in 1970 and 1971 in the western part of the Santa Barbara Channel and the northern Channel Islands than in the eastern part of the channel. Several earthquakes occurred along the northern edge of the deeper part of the Santa Barbara Basin, but only a few scattered earthquakes were located near the islands. South of Santa Rosa Island, a group of epicenters was centered on the northwestern part of the Santa Rosa-Cortes Ridge. A few also are located along the northern edge of the Santa Cruz Basin and near the hypothetical projection of the surface trace of the Santa Monica-Malibu Coast fault system.

In order to determine the focal depth of earthquakes accurately, at least one seismograph station must be located within a few kilometers of the epicenters. As the nearest stations are about 20 km from most earthquakes in the Santa Barbara Channel, precise calculation of their focal depths is not possible. However, accurate focal depths have been obtained for a few earthquakes that occurred close to recording stations. These focal depths range from 5 to 15 km, and are similar to depth values determined in central California.

Inasmuch as the largest earthquakes in the channel region during 1970 and 1971 have magnitudes of less than 4, fault-plane solutions for *individual* earthquakes are not feasible because of insufficient first-motion data. Figure 8 shows a fault-plane solution based on a composite plot of first-motions of *P* arrivals from 10 earthquakes on the inferred offshore fault west of the Oak Ridge Fault. All of these earthquakes occurred on May 7, 1971 (from 01:22 to 18:36) with very closely spaced epicenters (Table 2). Of the two possible fault planes, the one that strikes N77°E, dips about 70°N, and indicates left-lateral slip

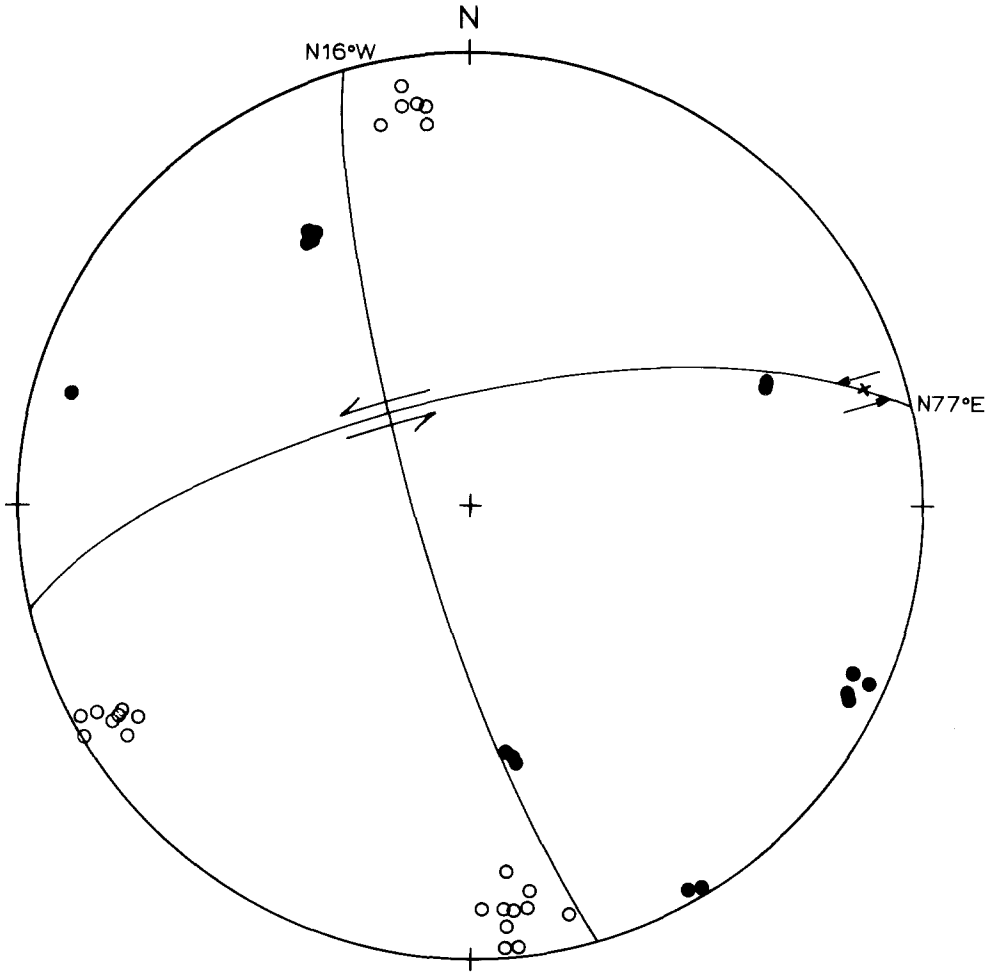

FIG. 8. Fault-plane solution constructed from composite first-motions of 10 earthquakes. Diagram is an equal-area projection of the lower focal hemisphere. Dots indicate compression; circles, dilatation. Small x is the projection of the slip vector with direction of motion indicated by arrows.

motion agrees favorably with some of the known and inferred fault orientations and movement directions in the region. However, it does not fit the reverse-slip and south-dipping relations observed along the Oak Ridge Fault. Our result differs significantly from that reported by Sylvester *et al.* (1970), who interpreted right-lateral oblique-slip movement along a northwest-striking fault for the earthquake swarm of 1968, which occurred in the same general vicinity. Left-lateral strike slip commonly has been attributed to faults in the Santa Barbara Channel but has not been adequately demonstrated on the basis of geological evidence. Left-slip offsets have been recognized along the large median faults on Santa Rosa and Santa Cruz islands and along parts of the Santa Ynez Fault. On the other hand, most of the coastal faults display large reverse separations and, by implication, have significant components of dip slip.

CONCLUSIONS

Comparison of Figures 2 and 7 indicates that the recent earthquake activity in the Santa Barbara Channel is similar to that of the preceding 40 years. With an improved

seismic network, the more precisely located earthquake epicenters show linear trends that appear to be spatially related to offshore faults inferred from acoustic profiles. A fault-plane solution based on composite first motions of earthquakes clustered about the west end of an inferred fault (about 18 km south of Santa Barbara) indicates left-lateral, strike-slip motion along a steeply dipping fault plane that strikes almost east-west.

A 2-year period is too short a time to draw firm conclusions on the seismicity of the Santa Barbara Channel. The present study is limited by the small number of earthquakes recorded and by the lack of detailed knowledge concerning the crustal structure of the region. Focal depths of most earthquakes are poorly determined because of the shortage of close-in stations. A few ocean-bottom seismographs placed in the middle of the channel would greatly improve our ability to locate earthquakes with precision.

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References

Allen, C. R., P. St. Amand, C. F. Richter, and J. M. Nordquist (1965). Relationship between seismicity and geologic structure in the southern California region, *Bull. Seism. Soc. Am.* **55,** 753–797.

Buchanan, J. M., J. I. Ziony, and R. O. Castle, (1973). Recent elevation changes across part of the Transverse Ranges near Ventura, California (Abstract), *Geol. Soc. Am. Abstracts with Programs,* **5,** 17.

Curran, J. F., K. B. Hall, and R. F. Herron (1971). Geology, oil fields and future petroleum potential of Santa Barbara Channel area, California in *Future Petroleum Provinces of the United States—Their Geology and Potential, Am. Assoc. Petrol. Geol., Mem. 15(1),* 192–211.

Eaton, J. P. (1969). Hypolayr—a computer program for determining hypocenters of local earthquakes in an earth consisting of uniform flat layers over a half-space, *U.S. Geological Survey, Open-File Report,* 155 pp.

Geiger, L. (1912). Probability method for the determination of earthquake epicenters from the arrival time only (translated from Geiger's 1910 German article), *Bull. St. Louis Univ.* **8,** 56–71.

Hamilton, R. M., R. F. Yerkes, R. D. Brown, R. O. Burford, and J. M. DeNoyer (1969). Seismicity and associated effects, Santa Barbara region, *U.S. Geol. Survey Profess. Paper, 679-D,* 47–68.

Healy, J. H. (1963). Crustal structure along the coast of California from seismic refraction measurements, *J. Geophys. Res.* **68,** 5777–5787.

Hill, M. L. and T. W. Dibblee, Jr. (1953). San Andreas, Garlock, and Big Pine faults, California—a study of the character, history, and tectonic significance of their displacements, *Bull. Geol. Soc. Am.* **64,** 443–458.

Jennings, C. W. (1959). Geologic map of California, Olaf P. Jenkins, Editor, *Santa Maria Sheet,* California Division of Mines and Geology, Scale, 1 : 250,000.

Jennings, C. W. and R. G. Strand (1969). Geologic map of California Olaf P. Jenkins, Editor, *Los Angeles Sheet,* California Division of Mines and Geology, Scale 1 : 250,000.

Lee, W. H. K. and J. C. Lahr (1972). HYPO71: A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *U.S. Geological Survey, Open-File Report,* 100 pp.

Lee, W. H. K., M. S. Eaton, and E. E. Brabb (1971). The earthquake sequence near Danville, California 1970, *Bull. Seism. Soc. Am.* **61,** 1771–1794.

Lee, W. H. K., R. E. Bennett, and K. L. Meagher (1972). A method of estimating magnitude of local earthquakes from signal duration, *U.S. Geological Survey, Open-File Report,* 28 pp.

Page, B. M., J. G. Marks, and G. W. Walker (1951). Stratigraphy and structure of the mountains northeast of Santa Barbara, California, *Am. Assoc. Petrol. Geol. Bull.* **35,** 1727–1780.

Shor, G. G. and R. W. Raitt (1968). Seismic studies in the southern California continental borderland, *Intern. Geol. Congress, 20th Section* **9,** 243–259.

Sylvester, A. G., S. W. Smith, and C. H. Scholz (1970). Earthquake swarm in the Santa Barbara Channel, California, 1968, *Bull. Seism. Soc. Am.* **60,** 1047–1060.

Vedder, J. G. and R. D. Brown, Jr. (1968). Structural and stratigraphic relations along the Nacimiento fault in the southern Santa Lucia Range and San Rafael Mountains, California, in *Proc. Conf. Geol. Problems San Andreas Fault system, Stanford Univ. Publ., Univ. Ser., Geol. Sci.* **11,** 242–259.

Vedder, J. G., H. D. Gower, H. E. Clifton, and D. L. Durham (1967). Reconnaissance geologic map of the central San Rafael Mountains and vicinity, Santa Barbara County, California, *U.S. Geological Survey, Misc. Geol. Inv. Map I-487.*

Vedder, J. G. and others (1969a). Geology, petroleum development, and seismicity of the Santa Barbara Channel region, California, *U.S. Geol. Surv. Profess. Paper, 679,* 77 pp.

Vedder, J. G., H. C. Wagner, and J. E. Schoellhamer (1969b). Geologic framework of the Santa Barbara Channel region, *U.S. Geol. Surv. Profess. Papers 679-A,* 1–11.

Weaver, D. W., and others (1969). Geology of the northern Channel Islands, *Pacific Section, Am. Assoc. Petrol. Geol. and Soc. Econ. Paleontologists Mineralogists, Spec. Publ.,* 199 pp.

Ziony, J. I., C. M. Wentworth, J. M. Buchanan, and H. C. Wagner (1973). Preliminary map showing recency of faulting in coastal southern California, *U.S. Geol. Surv., Misc. Field Studies Map,* in press.

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