Earthquake sequences and seismicity of the Watsonville Region of Central California

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Summary. — The Watsonville area designates here the region of Central California between the latitude 36°40′ and 37°05′ N and the longitudes 121°25′ and 121°50′ W. This area can be considered as a regional seismic unit. The seismic activity during the years 1960-1966 gives a background level of 2 or 3 earthquake of magnitude $2 < M \leqslant 3$, per month, with periods of increased activity associated with the occurrence of larger shocks. The presence and nature of sequences of earthquakes in the area is investigated for the period 1952-1966. Three sequences in 1963 are studied in more detail. Tentatively the sequences of the area are grouped in three general types.

Riassunto. — Con la denominazione di area di Watsonville si intende qui la regione della California situata tra i 36°40′ e 37°05′ latitudine N ed i 121°25′ e 121°50′ longitudine W. Tale area può essere considerata come unità sismica regionale. Negli anni 1960-1966, l'attività sismica offre un quadro di 2 o 3 terremoti di magnitudo $2 < M \leqslant 3$, al mese, con periodi di più intensa attività associata al verificarsi di scosse più ampie. Viene studiata la presenza e la natura dei fenomeni sismici nell'area predetta durante il periodo 1952-1966, e si fa un esame più particolareggiato di tre periodi sismici avvenuti nel 1963. A titolo di prova si sono raggruppati in tre tipi generali, i periodi sismici osservati nella stessa area.

Introduction.

The Watsonville region designates here the area between the latitudes 36°40′ and 37°05′ and the longitudes 121°25′ and 121°50′.

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This area covers a section of the San Andreas fault and is ideally suited for a detailed study of regional seismic conditions because it is covered by a net of permanent and mobile stations operated by the University of California. The geology of the area is of rather complex nature as shown in Figure 1 (Jennings and Strand, 1958).

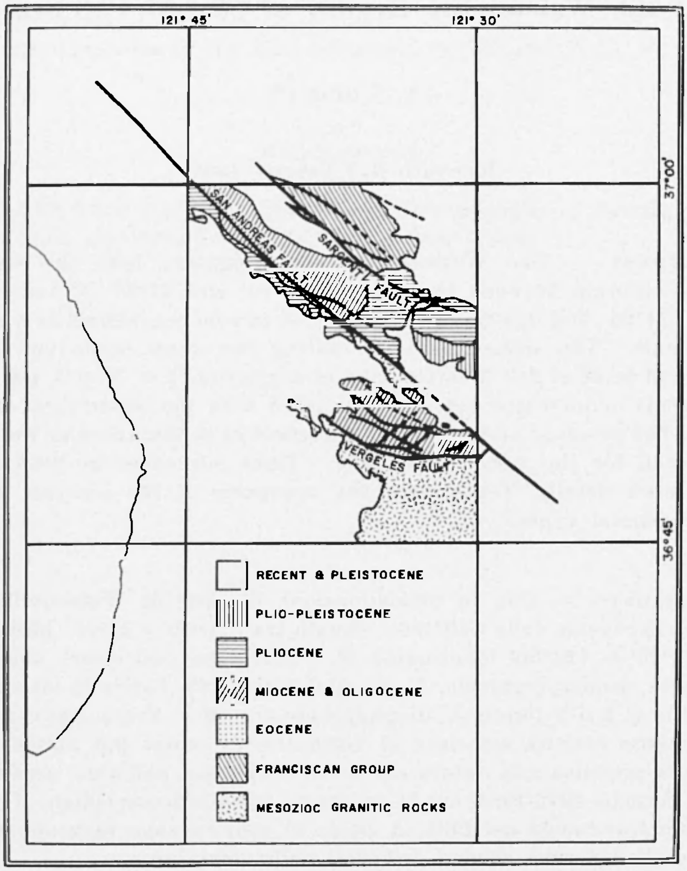

Fig. 1 – Generalized geological map of the Watsonville area (after J. E. Allen).

The main geological feature is the San Andreas fault which crosses the area striking N 47° W. Most of the area to the West of the fault is covered with alluvial deposite and Pleistocene non-marine sediments. Northeast of the fault the sediments are Oligocene and Miocene marine sediments. This part is traversed by a series of faults which trend parallel to the San Andreas of which the Sargent fault is the most important. The northern part of the granitic mass forming the Gabilan Range is at the southeastern end of the area, to the southwest of the San Andreas fault. At the north edge of the granitic outcrop there is a series of criss-crossing faults offshooting from the San Andreas in northwest and southwest directions.

Location of Permanent and Mobile Seismographic Stations.

In the region under study, there is a concentration of recording stations. Besides the permanent stations of Vineyard (VIT), Santa Cruz (SCC), Mount Hamilton (MHC), Llanada (LLA), and Paraiso

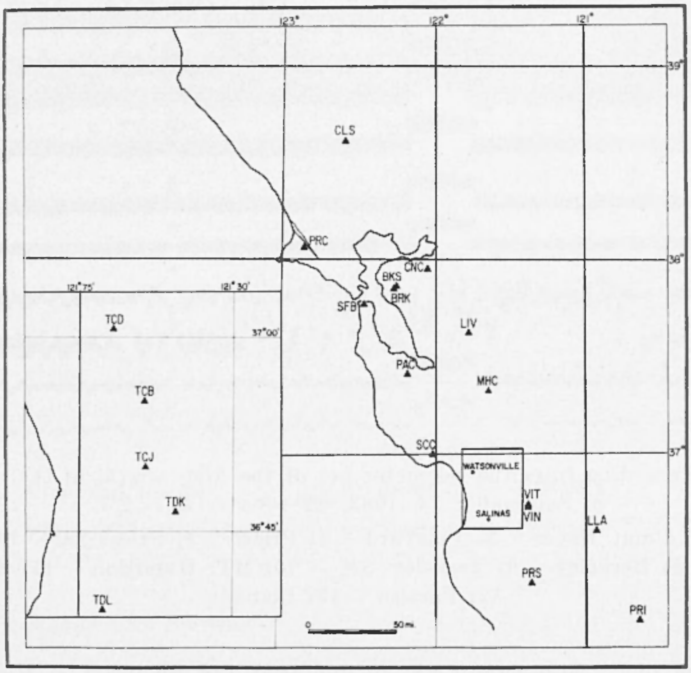

Fig. 2 – Map of Northern California showing the locations of permanent and mobile seismographic stations operated by the University of California.

(PRS), which surround the area, three mobile stations were used, since 1963, during the time following the main shocks and placed in the immediate area. Figure 2 shows the location of the permanent stations and some of the sites where the mobile units were installed. These stations are part of the telemeter net opereted by the University of California. They are equipped with short-period vertical Benioff

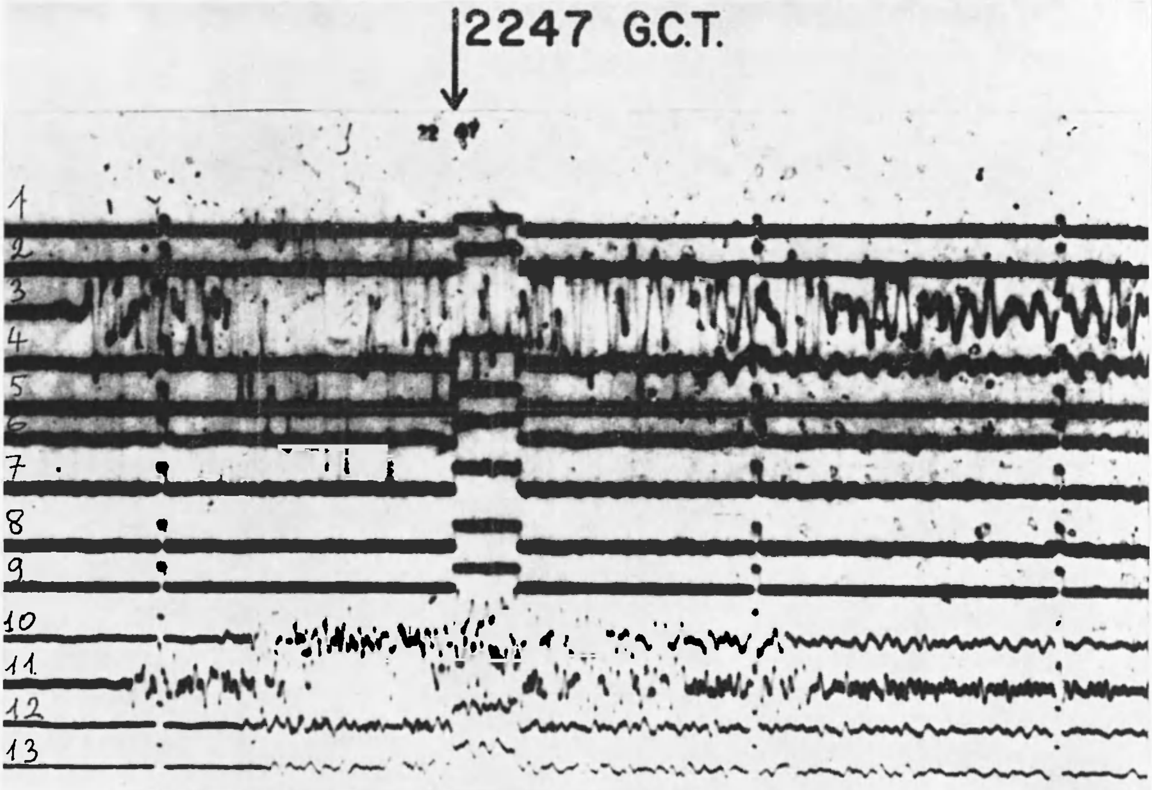

Fig. 3 – Recording from the telemeter net of the first arrival of the aftershock of September 14, 1963, $22^h 46^m 41^s$. $M = 2.5$.
1) Radio – 2) Point Reyes – 3) Vineyard – 4) Priest – 5) Priest SM – 6) Calistoga – 7) Concord – 8) Berkeley – 9) Berkeley SM – 10) MT. Hamilton – 11) Santa Cruz – 12) Paraiso – 13) Llanada.

seismographs. The signals are telemetered and recorded at Berkeley. The peak magnification of the instruments ranges from 100,000 to 200,000 at a period of about 0.3 seconds. Examples of the recording for the aftershock of September 14, 1963; $22^h 46^m$, are in Figure 3. Each mobile station is also equipped with a vertical short-period Benioff seismograph. The instruments were run at a peak magnification ranging from 15,000 to 40,000.

TABLE I — UNIVERSITY OF CALIFORNIA SEISMOGRAPHIC STATIONS IN OPERATION 1963.

Station Symbol	Station Name	Latitude North	Longitude West	Elevation (meters)
	Permanent Stations			
ARC	Arcata	40°42.6′	124°04.5′	59
BRK	Berkeley (Haviland)	37°52.4′	122°15.6′	81
BKS	Berkeley (Byerly)	37°52.6′	122°14.1′	276
CLS	Calistoga	38°38.2′	122°35.1′	457
CNC	Concord	37°58.1′	122°04.3′	36
FRE	Fresno	36°46.0′	119°47.8′	88
LLA	Llanada	36°37.0′	120°56.6′	475
MHC	Mt. Hamilton	37°20.5′	121°38.5′	1282
MIN	Mineral	40°20.7′	121°36.3′	1495
PAC	Palo Alto	37°25.0′	122°10.9′	83
PRC	Point Reyes	38°04.8′	122°52.0′	404
PRI	Priest	36°08.5′	120°39.9′	1187
PRS	Paraiso	36°19.9′	121°22.2′	363
SCC	Santa Cruz	37°00.4′	121°59.8′	128
SFB	San Francisco	37°46.6′	122°27.1′	100
SHS	Shasta	40°41.6′	122°23.5′	312
VIN	Vineyard (local)	36°45.0′	121°23.1′	330
VIT	Vineyard (telemeter)	36°45.0′	121°23.3′	380
	Mobile Unit Stations			
TCB	Chamberlain	36°55.9′	121°39.4′	240
TCD	Mt. Madonna	37°00.7′	121°42.3′	564
TCJ	Dorney	36°50.1′	111°38.7′	207
TDK	Sugarloaf	36°46.5′	121°35.7′	79
TDL	Merrill	36°37.9′	121°42.9′	18

The truck sites designated as TCB and TCJ were occupied through the period corresponding to the May 1963 sequence. The locations TCJ, TDL and TDK were used during the time covering most of the August and September, 1963 sequences. The coordinates of the permanent and mobile stations are given in Table I. The mobile station at Dorney (TCJ) which occupies the central part of the area was kept in continual operation from September 1 to October 25 (except for September 6), of 1963 providing and excellent coverage of the activity in the area. The station was kept in operation until the activity had returned to the normal level in order to check on the frequency of occurrence of small earthquakes.

Completeness of a Set of Earthquakes.

Earthquakes are events that can be specified by five parameters, x, y, z, t, E (3). The parameters x, y, z specify the spatial location of the focus of the earthquake; x, y refer to the latitude and longitude of the epicenter and z to the depth of focus; t specifies the origin time and E the energy released as elastic waves. This last parameter can be interchanged with M, the magnitude, as defined in the conventional manner. An earthquake, thus considered, constitutes a point in a five-dimensional space (x, y, z, t, E).

A helpful concept in the study of seismicity is that of a complete set of earthquakes. We mean by a complete set of earthquakes a set containing every earthquake that occurred within given boundaries of the five parameters already specified. The boundaries on x, y, and z depend on the region under study. The boundaries on t specify the period of time which is covered by the analysis. The boundaries on E (or M) are a function of the sensitivity and coverage of the recording stations in the region and period of time under consideration. The lower limit must be quantitatively determined from the actual distribution of stations in the area so that all earthquakes above this lower limit are recorded. This idea is of special interest in discussions dealing with the frequency of occurrence of small earthquakes.

The boundaries for the set of earthquakes in this study are the following:

x between 36°40′ and 37°05′
y between 121°25′ and 121°50′
z less than 20 km.

The limit on z is based on the depth found for all the earthquakes of this area for which there is sufficient information.

The limits on M depend on the period of time under study. For the time intervals when only the permanent stations of the telemeter net were in operation the lower magnitude for which an earthquake could be located in this region is of the order of $M = 2.2$. For the time intervals when the mobile stations were in operation the lower limit can be reasonably set to $M = 1.0$. This applies, for example, to the periods May 7 to 17, and August 31 to October 25, 1963. A higher limit on M than that given by the sensitivity of the operating stations can be arbitrarily selected depending on the magnitude level of the seismic activity in which one is interested.

This concept of the completeness of a set of earthquakes is of particular importance when studying the frequency of occurrence of earthquakes with time and magnitude. Analyses of earthquake sequences have sometimes been made when there is no certainty that the actual number of earthquakes with given magnitude is the same as the number of recorded earthquakes with that magnitude. In our analysis a lower limit of magnitude is always assigned above which the recorded earthquakes form a complete set.

Seismicity of the Watsonville Region, 1960-1966.

The seismicity activity of the region has been studied during the seven years period from 1960 to 1966. This period has been divided into two, the first including the years 1960 to 1963, and the second from 1964 to 1966.

Seismicity 1960-1963.

For this interval the seismic activity of the region above the 2.5 magnitude level has been studied. Above this magnitude level, the earthquakes in this region and period of time constitute a complete set.

The linear plots of frequency and magnitude versus time for the whole period are given in Figure 4. A number of significant features are noticeable:

(a) There is a continuous activity of about two to three earthquakes of magnitudes between 2.5 and 3.5 per month.

(b) There is a fair correlation between the peaks of the frequency plot and those of the magnitude.

(c) For every earthquake of magnitude greater than 4.0 there is a corresponding peak in the frequency plot.

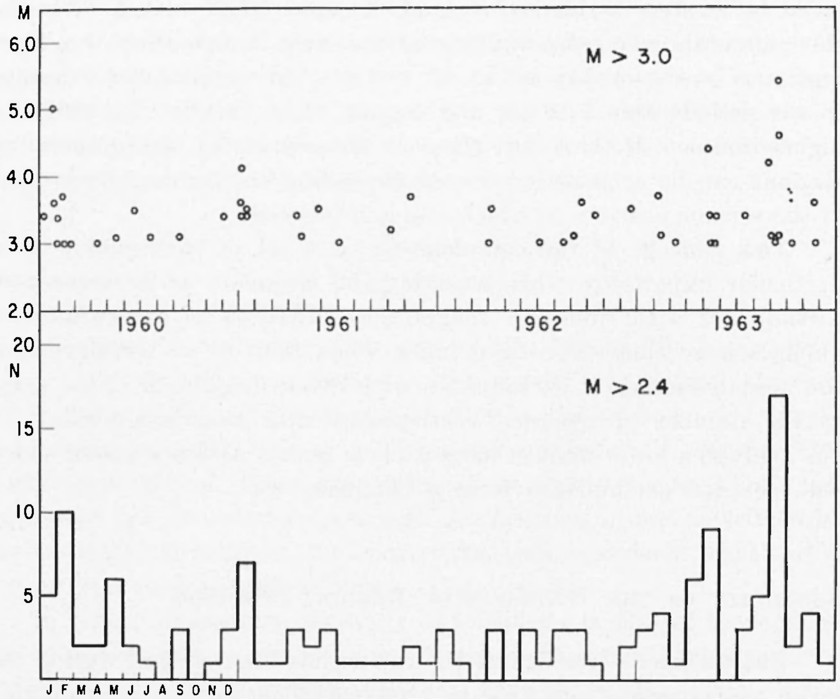

Fig. 4 – Magnitude and frequency versus time for earthquakes in the Watsonville region during the period 1960 to 1963 inclusive.

These features seem to indicate that for this region and time interval, earthquakes of magnitude 4 and above did not occur singly, but as part of a sequence, either a classical aftershock sequence or a swarm of earthquakes. The four most prominent peaks in the frequency plot correspond to the occurrence of the earthquakes of January 20, 1960; January 4, 1961; May 7, August 31, and September 14, 1963. The entire period shows a continuous level of background activity of 2 to 3 earthquakes of magnitude between 2.5 and 3.5. per month. The region was at this level of activity from January 1961 to February 1963.

To combine the information given in the plot of frequency and magnitude versus time, the energy of the earthquakes which occurred in one month was summed and its logarithm multiplied by N, the number of earthquakes. The quantity F, defined as

$$F = N \log \sum_{i=1}^{N} E_i$$

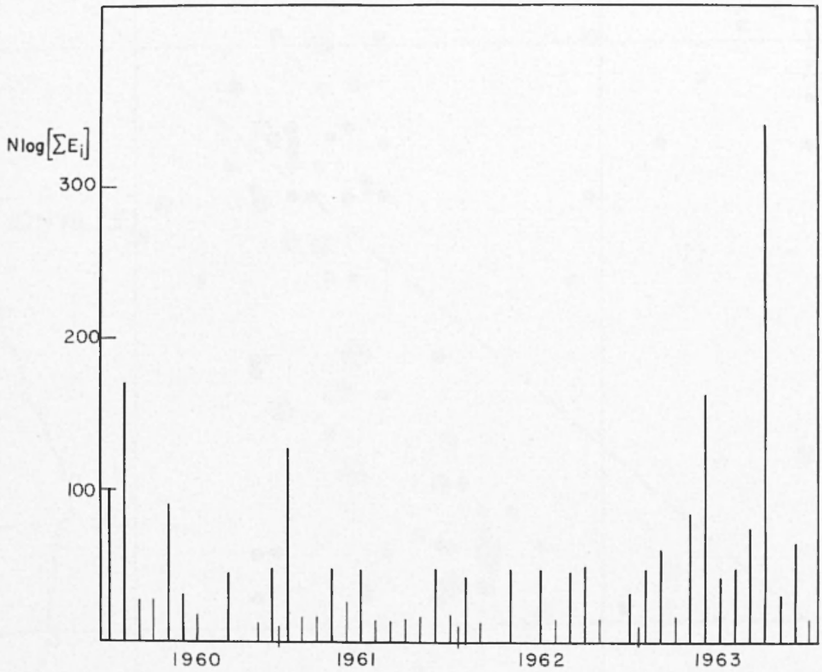

Fig. 5 – Plot of $N \log \sum_{i=1}^{N} E_i$ versus time, for the period 1960-1963.

has been plotted in Figure 5 for this period. This kind of plot, although it has no direct physical interpretation, serves to emphasize the occurrence of large number of earthquakes per unit time connected with the occurrence of a large earthquake. The plot also gives a good representation of the background seismic activity. The large peak at September 1963 is due to the already mentioned occurrence of the two sequences.

This discussion has been carried out for earthquakes of magnitude greater than 2.5. The relation between frequency and magnitude for smaller earthquakes has been studied for 1963. In this year, because

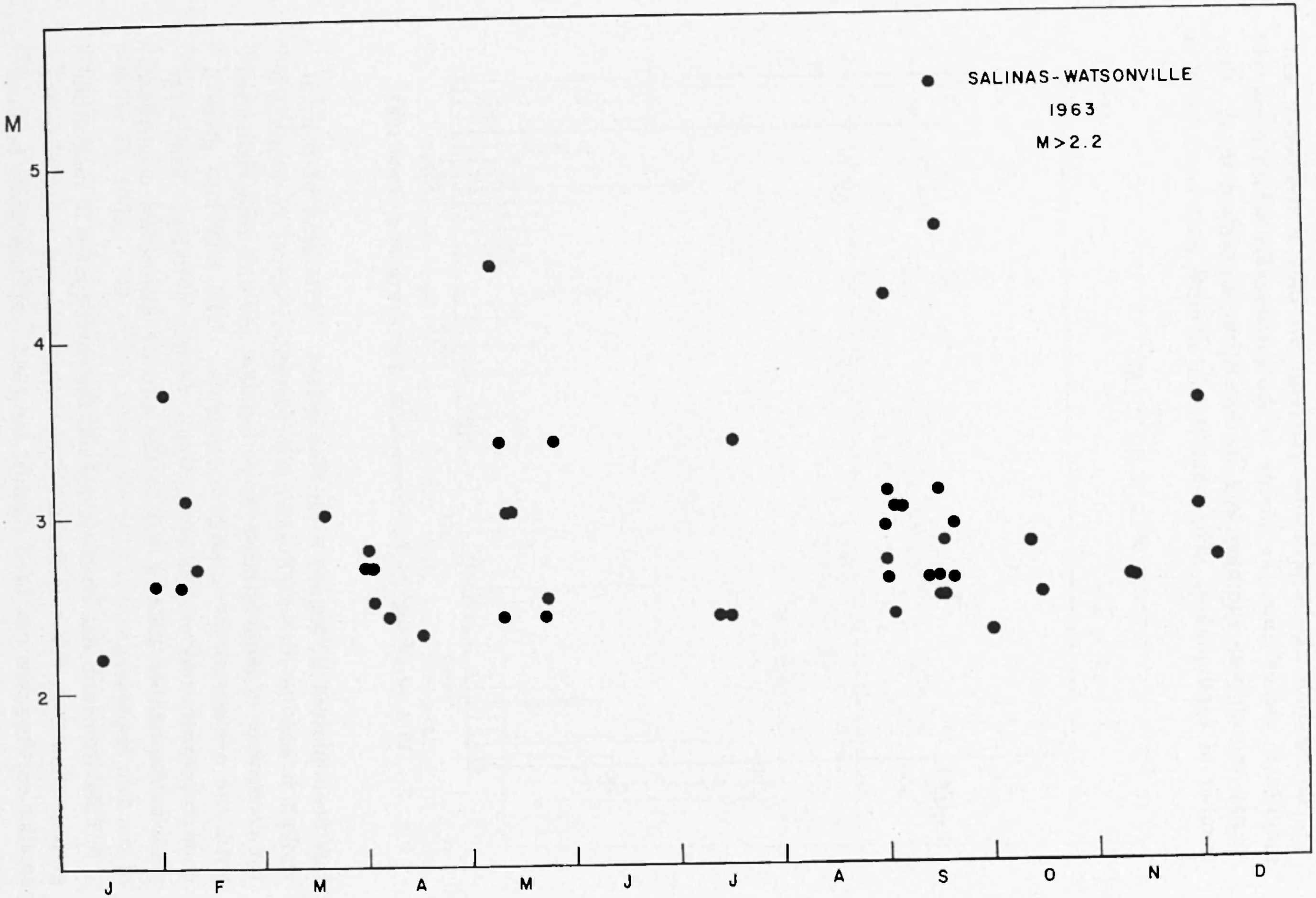

Fig. 6 – Plot of magnitude versus time during the year 1963 for $M \geqslant 2.2$, in the Watsonville region.

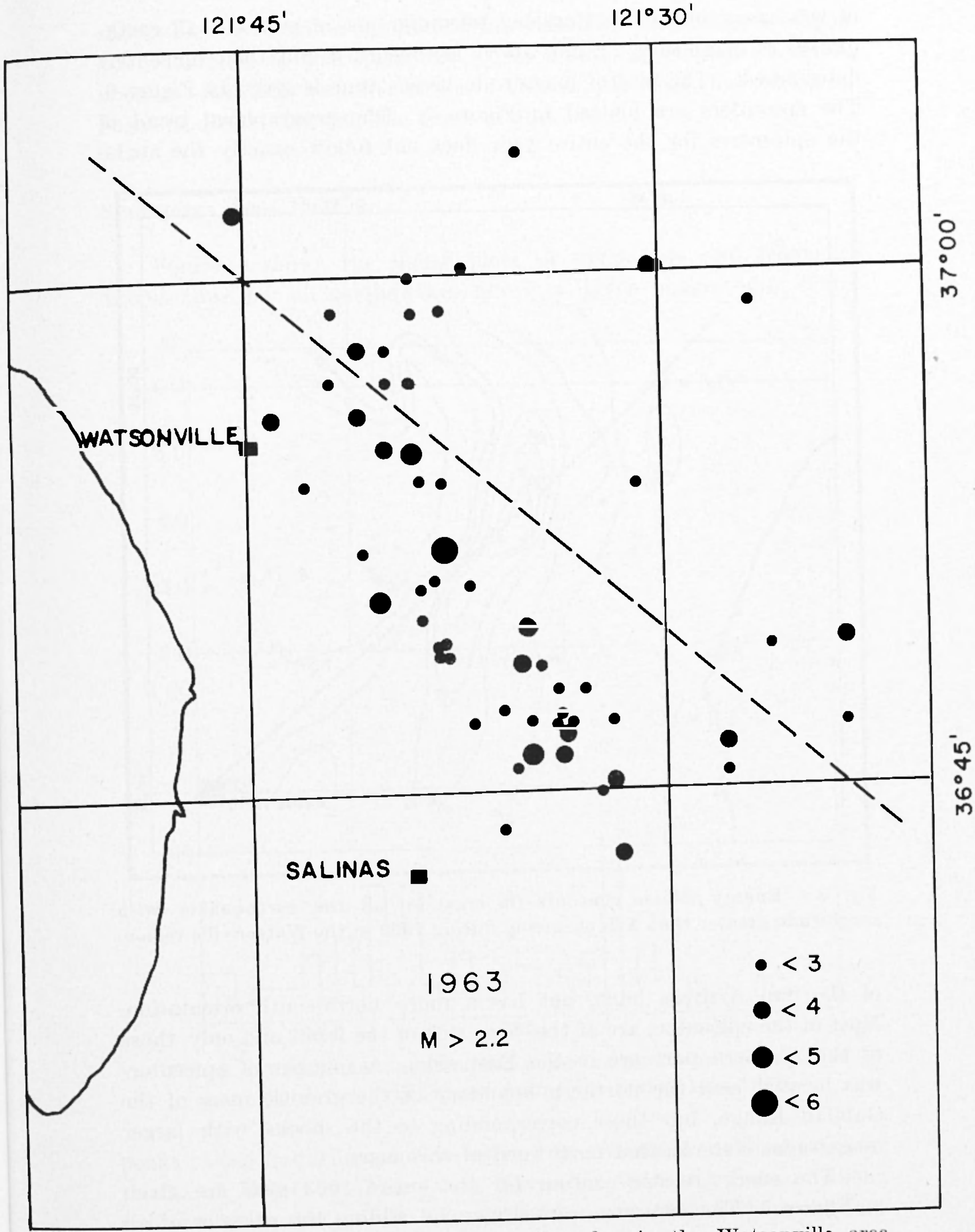

Fig. 7 – Epicenter location of the earthquakes in the Watsonville area during 1963. $M \geqslant 2.2$. The number refer to magnitude.

of the operation of the Berkeley telemeter net of stations, all earthquakes of magnitude 2.2 and above are recorded and their epicenters determined. The plot of magnitude versus time is given in Figure 6. The epicenters are plotted in Figure 7. The geographical trend of the epicenters for the entire year does not follow exactly the strike

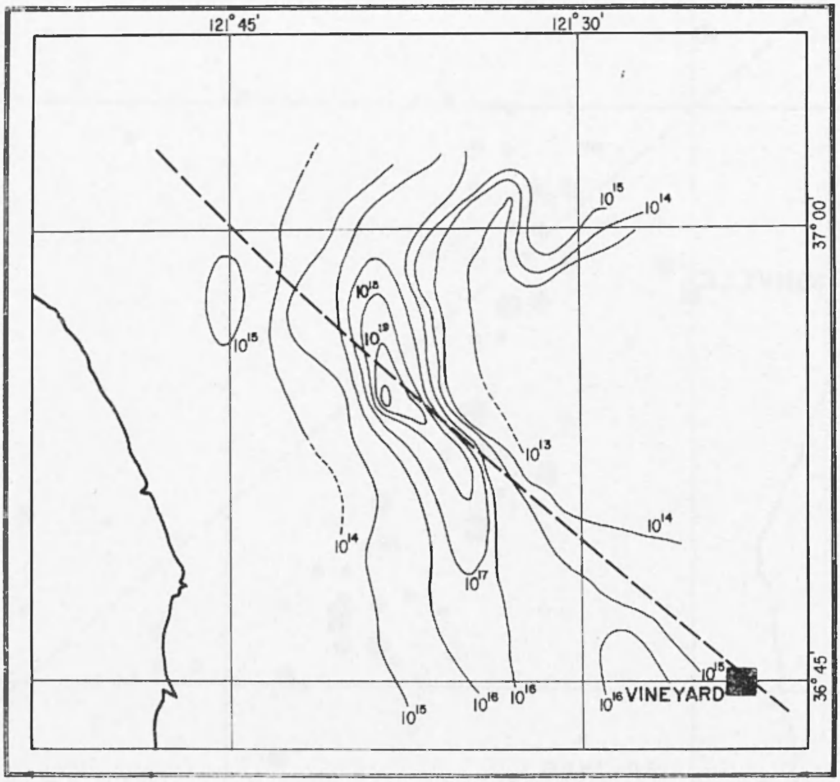

Fig. 8 – Energy release contours (in ergs) for all the earthquakes with magnitude greater than 2.2, occurring during 1963 in the Watsonville region.

of the San Andreas fault, but has a more north-south orientation. Most of the epicenters are at the West side of the fault, and only those of the northern part are in the East side. A number of epicenters was located near the northern boundary of the granitic mass of the Gabilan Range, but those corresponding to the shocks with larger magnitudes were located northward of this mass.

The energy-release contour for the entire 1963 year are given in Figure 8. The contours were drawn by adding the energies of all shocks located within a square of 5 km side. The contour lines emphasize the trend of the epicenters. This trend, as mentioned before, does not coincide with the strike of the San Andreas, but makes an angle of about 20° with the trace of the fault.

Seismicity 1964-1966.

Figure 9 shows the linear plots of magnitude and frequency versus time for all earthquakes above a given magnitude. Three

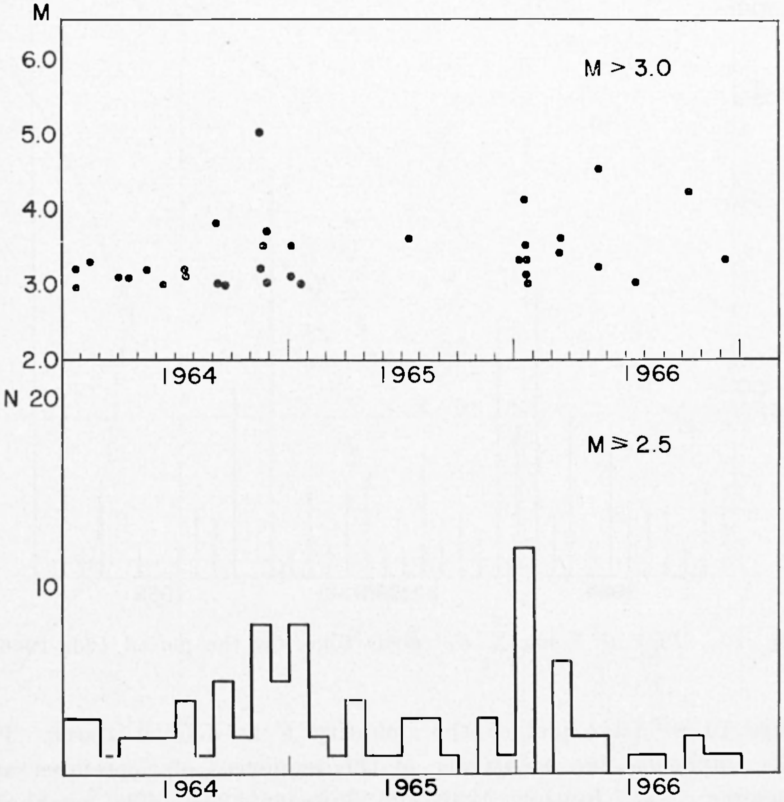

Fig. 9 – Magnitude and frequency versus time for earthquakes in the Watsonville region during the period 1964-1966.

peaks in the frequency plot correspond to aftershocks related to main shocks of M greater than 4.0 in November 1964 and January 1966; and to a main shock with $M = 3.5$ in January 1965. There are two shocks with magnitude 4.5 and 4.2 which were not followed by any increase in the seismic activity at least at the level of $M \geqslant 2.5$, level at which our analysis was made. If these shocks were followed by aftershocks must have been all of very small magnitude, and less than 2.5. During 1965 the seismic activity was at a low level. In

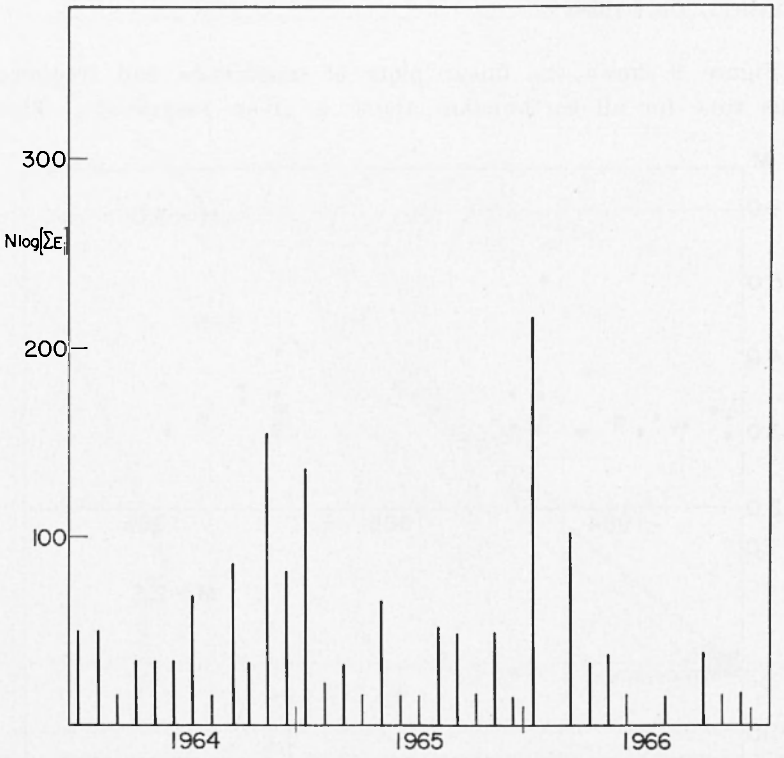

Fig. 10 – Plot of $N \log \sum_{i=1}^{N} E_i$ versus time, for the period 1964-1966.

Figure 10 we have plotted the quantity F as defined above. The peaks emphasize the occurrence of the sequences of September and November 1964, January 1965 and January 1966. The peak corresponding to March 1966 does not correspond to a sequence in the usual sense, but to an increase of activity during a ten days period from March 7 to 16, and located in the central area around 36°48′, 121°35′. Outside these periods, the level of the background seismic activity for the area is of 1 to 3 earthquakes above $M = 2.5$ per month. This agrees with the results from the precedent period.

Figure 11 shows the location of the epicenters ($M > 2.5$) for the three years. Comparing with the location of the epicenters of 1963 (Fig. 7) we notice the same concentration of epicenters southwest

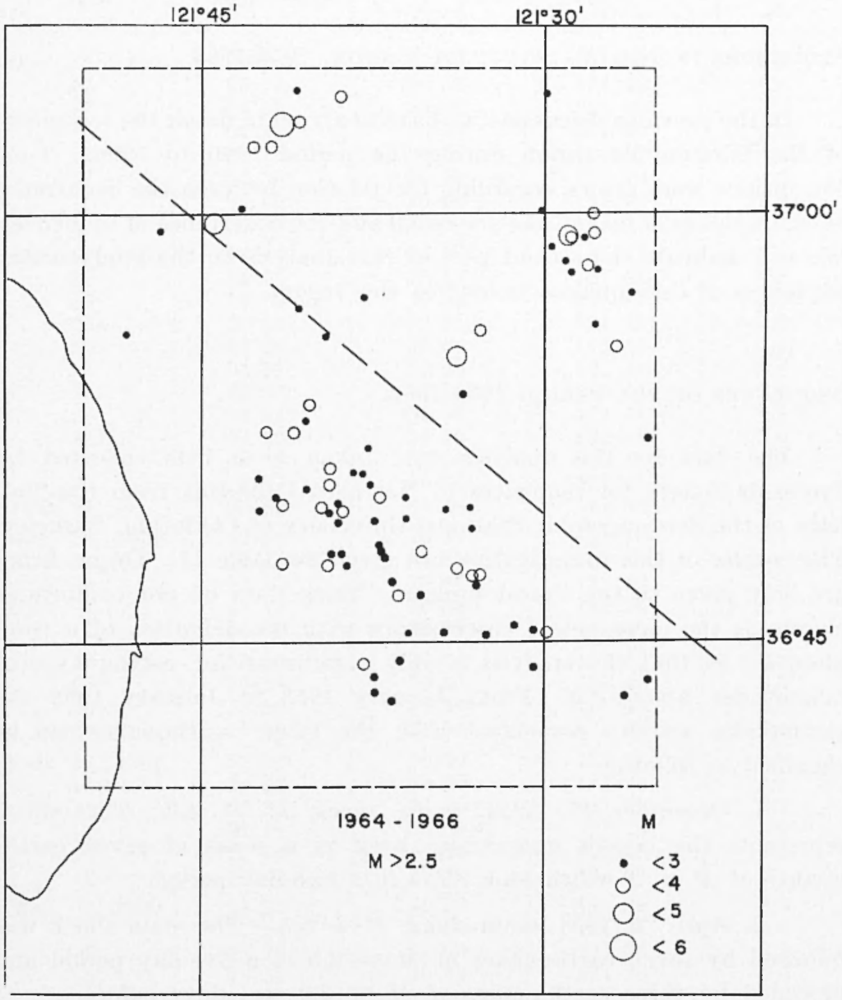

Fig. 11 – Epicenter location of the earthquakes in the Watsonville region during the period 1965-1966.

of the San Andreas fault in the central part of the region. Besides, there are two clusters of epicenters corresponding to the sequences of November 1964 (Corralitos series) and January 1966 (San Felipe Lake series) in the northeast side of the fault. Outside the shocks related to these two series almost all the other earthquakes occurred in the area southwest of the San Andreas, with the exception of the two shocks with $M > 4.0$ occurred in 1966 and not followed by any series.

Sequences in the Watsonville Region, 1953-1966.

In the previous discussion we have analysed in detail the seismicity of the Watsonville region during the period 1960 to 1966. Some conclusions were drawn regarding the relation between the occurrence of earthquakes of magnitude above 4.0 and the occurrence of sequences. We will dedicate the second part of this analysis to the study of the sequences of earthquakes located in this region.

Sequences of the period 1953-1962.

The data for this analysis were taken from lists collected by Professor Byerly for sequences in Northern California from the Bulletin of the Seismographic Stations, University of California, Berkeley. The results of this investigation are given in Table II. Origin times are only given to the closest minute. These data do not conform as closely as the more recent observations with the definition of a complete set so that the analysis is only significant for earthquakes of magnitudes above 3.0. From January 1953 to January 1963 the earthquake activity associated with the larger earthquakes can be classified as follows:

1. December 17, 1953, main shock $M = 4.2$. This shock represents the largest magnitude shock in a series of seven earthquakes of $M > 3$ which took place in a two-day period.

2. April 25, 1954, main shock $M = 5.3$. The main shock was followed by seven earthquakes of $M > 2.5$ in a five-day period and preceded by three earthquakes of $M > 3.0$ two days before.

3. December 1, 1956, main shock $M = 4.4$. No appreciable increase recorded in the occurrence of earthquakes immediately before or after.

4. June 26, 1957 and December 10-12, 1957. Two swarms of earthquakes of magnitude between 2.0 and 3.5, not connected with any shock of greater magnitude.

Table II – SERIES OF EARTHQUAKES IN THE WATSONVILLE AREA DURING THE PERIOD 1950-1961.

Date	Origin Time	Latitude Nord	Longitude West	Magnitude M
Dec. 15, 1953	00h05m	36°55′	121°39′	3.5
16	23 10	36 55	121 40	3.8
17	04 50	36 55	121 40	3.7
17	04 57	36 55	121 40	2.6
17	05 13	36 55	121 40	4.2
17	05 39	36 55	121 40	4.6
17	06 59	36 55	121 40	3.5
28	01 33	36 55	121 37	3.8
Apr. 22, 1954	18 44	36 57	121 41	3.8
22	18 50	36 57	121 41	4.3
22	19 09	36 57	121 41	3.0
25	20 33	36 56	121 41	5.3
25	21 25	36 56	121 41	3.5
26	01 32	36 56	121 41	2.8
26	02 35	36 56	121 41	2.6
26	04 04	36 56	121 41	2.3
26	04 53	36 56	121 41	3.0
28	04 58	36 56	121 41	2.5
30	18 27	36 56	121 41	
June 12	03 52	36 56	121 38	2.5
Oct. 10, 1956	12 54	36 51	121 46	3.1
Nov. 5	20 14	36 49	121 37	3.0
8	03 41	36 47	121 40	3.0
Dec. 1	14 11	36 52	121 36	4.4
11	16 02	36 53	121 33	3.0
June 26, 1957	13 09	36 54	121 40	2.2
26	13 28	36 54	121 40	2.3
26	13 50	36 54	121 40	2.2
26	16 20	36 54	121 40	2.4
Dec. 10, 1957	23 06	36 50	121 28	3.0
10	23 22	36 50	121 28	2.8
11	00 31	36 50	121 28	2.4
11	01 41	36 50	121 28	3.0
11	23 46	36 50	121 28	3.2
12	00 18	36 50	121 28	2.4
Mar. 2, 1959	23 27	36 59	121 36	5.3
3	07 24	37 00	121 36	4.4
3	08 20	37 00	121 36	3.1
3	18 32	36 59	121 36	4.0
4	06 25	37 00	121 36	3.2
4	08 02	37 00	121 37	3.8
4	08 57	37 00	121 37	3.0
4	20 55	37 00	121 37	3.5
4	21 06	37 00	121 36	3.6
10	00 19	36 59	121 35	3.5
Jan. 20, 1960	03 25	36 47	121 26	5.0
20	03 47	36 47	121 26	3.6
20	13 12	36 50	121 28	2.7
25	05 52	36 48	121 42	2.9
Jan. 3, 1961	23 00	36 52	121 40	3.6
4	00 30	36 52	121 40	4.1
7	03 21	36 59	121 30	3.4

5. March 2, 1959, main shock $M = 5.3$. The main shock was followed by nine earthquakes $M > 3.0$ in a two-day period.

6. January 20, 1960, main shock $M = 5.0$. The main shock occurred outside the defined area, and only some of the aftershocks occurred inside the area.

7. January 3, 1961, main shock $M = 4.1$. The activity increased at the 2.0 level at the time of occurrence of the main shock.

The conclusions are: (a) there were four earthquakes with $M > 5.0$ in ten years, all of them followed by sequences of aftershocks. (b) There were five earthquakes with $4.0 < M < 5.0$ which were not associated with any of the sequences started by the magnitude 5.0 earthquakes; of these, at least three were followed by aftershocks.

The argument about a threshold magnitude of about 4 for the main shock in a sequence is not complete here. We do not have data for this period which will detect and identify earthquakes at the $M = 2.0$ level and below, and earthquakes of magnitude about 4 are more likely to be followed by aftershocks of magnitudes lower than 3.0 which is the limit of the magnitude detectable. It is likely, therefore, that a shock such as that of December, 1, 1956 could have occurred in a sequence.

Sequences of 1963.

Three sequences occurred in this year and are studied separately since more refined data were available for them because of the use in this time of mobile stations which made possible the detection of earthquakes down to magnitudes of the order of $M = 1.0$.

The first sequence occurred on May 7. The list of shocks identified as belonging to this sequence is given in Table III. The main shock of magnitude 4.4 occurred on May 7, $07^h07^m47^s$; the number of shocks during May 7 and 8 is small and they are of small magnitudes. This number inreases during May 9 and decreases sharply during the following 10 days. The epicenters of those earthquakes which were recorded by enough stations to allow an accurate location are shown in Figure 12. The spread of the epicenters is quite large. The shocks designated with the numbers 18 and 35 in Table III do not seem to belong to the sequence. In the linear plots of the magnitude and frequency versus time, given in Figure 13, we can see that in this case the peak of the frequency plot occurs three days after

Table III – EARTHQUAKES FROM MAY 7 TO MAY 22, 1963 FOR THE WATSONVILLE REGION.

Nº	Data	Origin Time	Latitude Nord	Longitude West	Dephi km	Magnitude M
1	May 7 1963	07h07m47.4s	36°50.5′	121°40.4′	5.93	4.4
2		70 12				
3		08 41				
4	8	00 06				
5		02 04				
6	9	02 51				
7		09 32				
8		12 00 08.9	36 45.5′	121 28.1	5.92	2.0
9		12 04 19.1	36 46.2′	121 28.1	8.02	3.4
10		12 08				
11		12 25				
12		12 28				
13		13 33				
14		18 04				
15	10	02 23 56.6	36 51.1′	121 38.5	5.13	2.4
16		02 46				
17		07 39				
18		12 06 35.9	37 04.8′	121 35.8	7.7	
19	11	14 38				
20		22 53 44.4	36 49.8′	121 35.0	0.1	3.0
21		22 59				
22	12	00 56 19.6	36 48.6′	121 35.3	3.0	3.0
23		00 59				
24		13 31 20.4	36 52.6′	121 37.6	2.3	
25	14	00 55				
26		02 39				
27		19 00 50.9	36 50.1	121 26.9	3.0	
28	15	01 18				
29		01 32				
30		10 38				
31		10 41				
32	18	01 52				
33	22	10 18 28.4	36 48.6	121 34.6	0	2.4
34	23	19 43 45.8	36 47.4	121 36.0	3	2.5
35	24	08 04 20	37 02.6	121 45.6	9	3.4

the main shock. The connection of the shocks on May 9 with the main shock of May 7 is not very clear. The shape of the plots is quite different from the classical pattern of aftershocks sequences such as that found for the sequences of September, 1963. This sequence, although it was started by the occurrence of the earthquake of magnitude 4.4 on May 7, does not conform exactly to this pattern mainly because of the absence of activity later on May 7 and on May 8.

The other two sequences followed earthquakes occurred on August 31 and September 14; they were previously studied by the author ([12]).

The list of the earthquakes from August 31 to October 1 is given in Table IV. Only those earthquakes were located for which sufficient data for an accurate epicenter determination were available.

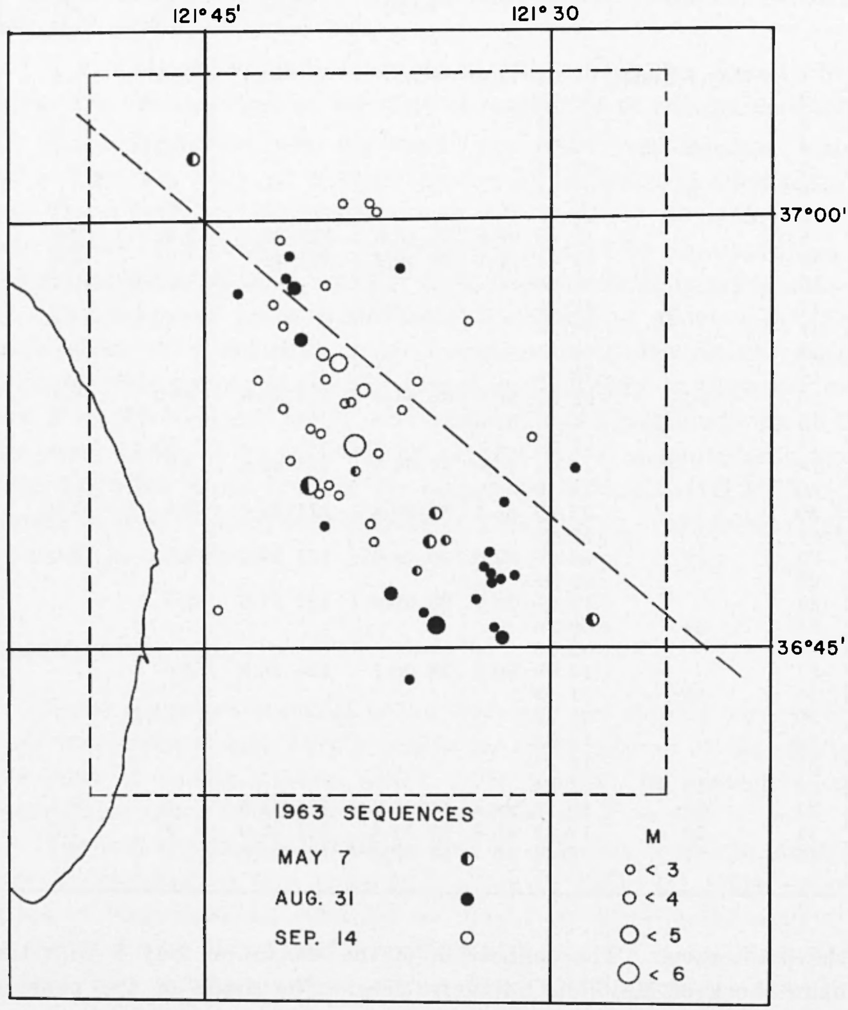

Fig. 12 – Adopted location of the earthquakes of the May 7, August 31 and September 14, 1963 sequences.

The epicenters and depth of these shocks were found using a special program (2) for a high-speed computer. The epicenters are believed to be accurate within about 2 km. Calculated estimates for the depth of the focus are in general less accurate.

The magnitudes were found from the recordings of the Wood-Anderson instruments at BRK, PAC, VIN, and MHC (cf. Table I). For earthquakes with magnitude smaller than 2.0, the magnitudes

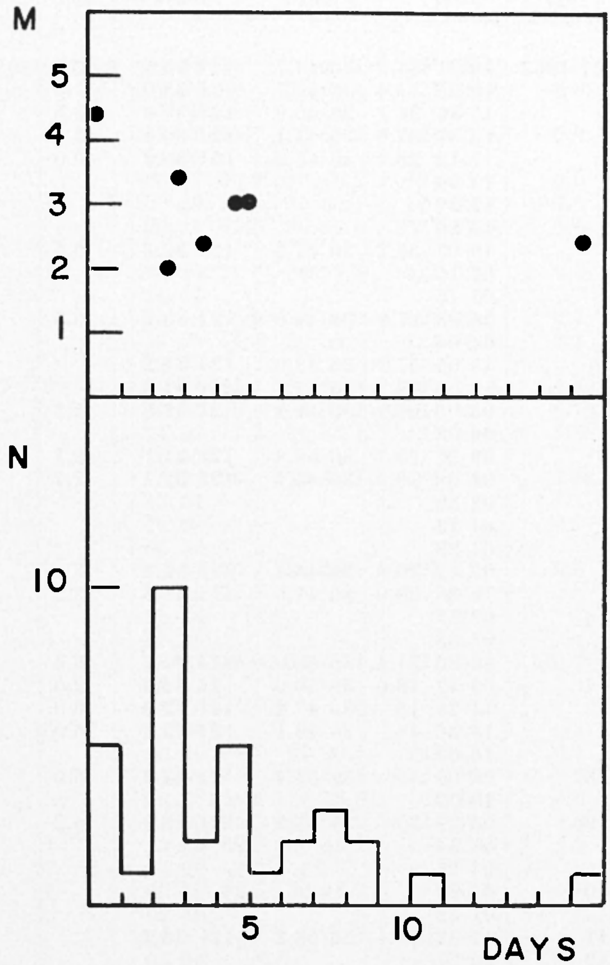

Fig. 13 – Magnitude and frequency versus time for the May 7, 1963 sequence.

were calculated from the maximum trace amplitude recorded by the Benioff instrument at TCJ (Dorney). In this calculation the amplitudes were reduced to the hypothetical response of a Wood-Anderson instrument with the same location.

TABLE IV – EARTHQUAKES FROM AUGUST 31 TO OCTOBER 1, 1963 IN THE WATSONVILLE REGION.

Nº	Date	Origin Time	Latitude Nord	Longitude West	Depth km	Magnitude M
1	Aug.31 1963	16h31m14.2s	36°45.7′	121°35.0′	2.3	4.2
2		16 35 17.0	36 47.7	121 33.0	1.6	2.6
3		16 35 34.1	36 46.9	121 37.0	3.5	3.0
4		16 37 07.6	36 44.1	121 36.4	3.7	2.7
5		17 12 26.7	36 45.8	121 35.2	0.0	2.7
6		17 34				1.2
7		17 37				2.0
8		17 38				1.3
9		19 07 36.2	36 47.3	121 32.3	6.5	2.4
10	Sept. 1	02 15				1.3
11		02 15				1.4
12		04 03 17.8	36 46.6	121 33.2	0.5	2.1
13		04 04				0.6
14		15 05 57.1	36 57.9	121 41.2		2.0
15		15 05 59.2	36 57.7	121 41.0		3.0
16	2	05 05 06.9	36 48.2	121 32.8	5.3	2.0
17		06 08				0.9
18		09 56 33.7	36 58.8	121 41.1	2.1	2.0
19	3	01 08 16.9	36 45.1	121 32.1	2.7	3.0
20		02 59				0.8
21		04 13				0.9
22		04 29				0.6
23		07 42 19.9	36 45.4	121 32.4	3.9	2.4
24		16 38 28.0	36 47.5	121 31.6	3.2	2.0
25	4	03 17				1.0
26		07 53				0.6
27		10 26 31.4	36 55.9	121 40.7	6.3	3.0
28	7	09 42 18.0	36 50.0	121 32.0	2.0	2.0
29		14 28 15	36 47.2	121 32.3	6.0	1.6
30		14 36 48	36 49.1	121 39.8	6.0	1.6
31		16 03				1.0
32	8	06 05 45	36 57.4	121 43.6	5.0	2.0
33		10 03				0.6
34	9	06 39 30	36 51.2	121 28,9	5.2	1.8
35		06 54				1.0
36		07 25				1.6
37	10	01 23				1.0
38		01 32				0.8
39	11	17 33 50.4	36 58.2	121 36.3		1.6
40	12	20 27				1.2
41	13	00 51				1.2
42		13 05 35.2	36 47.2	121 32.4	1.2	2.6
43		22 46				1.4
44	14	01 54				1.5
45		19 46 17.0	36 52.0	121 38.3	3.3	5.4
46		19 58 40.9	36 55.1	121 39.9	2.8	3.1
47		20 28 11.2	36 55.0	121 39.3	12.4	4.6
48		22 46 41	36 54.0	121 38.0	7.0	2.5
49	15	00 17 51	36 53.5	121 38.9	4.0	1.9
50		00 34 35.2	36 52.5	121 39.9	15.6	1.8

Table IV *(continuation)*

N°	Date	Origin Time	Latitude Nord	Longitude West	Depth km	Magnitude M
51	Sept 15 1963	01h46m10s	36°54.3′	121°42.6′	2.4	2.4
52		02 34 37	37 00.4	121 38.9	6.0	2.3
53		03 09				1.3
54		03 49 54.7	36 51.5	121 41.4	3.9	2.5
55		04 26				1.0
56		05 44 09.2	36 48.2	121 33.9	0.0	2.3
57		06 59 22.7	36 50.1	121 39.3	3.6	1.6
58		09 41 31.5	36 48.6	121 37.6	4.4	2.1
59		10 21				1.1
60		14 14 21.6	36 53.3	121 36.1	6.0	1.8
61		15 55				1.1
62		15 58 50.9	36 50.6	121 39.5	2.7	2.6
63		17 08 44.3	36 56.4	121 33.5	2.1	2.1
64		17 23				
65	16	00 51 45.1	36 57.0	121 42.0	4.8	2.3
66		00 55 36.6	36 57.7	121 39.7	6.5	2.8
67		01 32 11.5	36 56.1	121 41.6	5.9	2.0
68		10 55				
69		16 31 32	36 49.4	121 37.8	7.3	1.6
70		17 04				0.9
71		21 09				1.3
72	17	05 56				0.9
73		20 41 50	36 46.1	121 44.5	9.8	2.0
74		22 39				
75		23 45				1.1
76	18	11 36				1.6
77		12 51 46.0	36 55.4	121 25.5	10.7	2.0
78		20 42				0.7
79		22 48				1.4
80	19	02 15				1.0
81		06 20 44	37 00.7	121 37.8	9.1	1.6
82		09 58 01	36 44.3	121 35.7	9.2	1.6
83		12 16 28.3	36 53.6	121 38.7	4.6	2.9
84		18 36 05.0	37 00.2	121 37.6	5.8	2.6
85	21	13 29 58.9	36 59.2	121 41.6	8.9	2.4
86	22	11 20				1.5
87	24	00 35 42.5	36 46.7	121 33.8	5.6	1.6
88	25	02 46				0.7
89		02				1.1
90		05 26				1.6
91		11 08				
92		11 09				
93		11 17 47.9	36 52.7	121 40.2		1.9
94	26	10 32 28.2	36 63.1	121 41.7	11.4	1.9
95		10 46 05.4	36 54.3	121 39.8	4.1	2.2
96		23 08				1.3
97	27	23 53 30.8	36 51.7	121 37.4	4.7	2.2
98	30	11 29				1.3
99	Oct. 1	07 28 07.3	36 50.3	121 40.0	5.6	2.0
100		08 47 57.6	36 52.1	121 30.7	9.4	2.3

The location of the shocks are given in Figure 12. Some characteristics should be noted:

(a) The earthquakes of the first sequence are concentrated at the south end of the region with a few shocks at the north end. The gap between these two groups of the first sequence is filled by the aftershocks of the second sequence.

(b) About eighty per cent of the shocks occurred on the west side of the San Andreas fault. The general trend of the earthquakes of both sequences is oriented in a N 24° W direction. This direction intersect the trend of the fault at an angle of about 23 degrees. Because of the high accuracy in the determination of the epicenters, this trend must be considered as being significant. This trend coincides with the general trend of the epicenters in the region as was seen in the first part of this paper.

(c) The depths of the shocks range from 1 to 12 km, but most of them are between 3 and 6 km. No particular pattern was found in the depths, neither as to the time of occurrence, nor the location in relation to the San Andreas fault.

(d) All shocks with magnitudes over 4.0 lie on a narrow belt oriented in a northwest direction. The energy released decreases as the earthquakes separate from this belt.

A quantity which has been used often in describing the characteristics of earthquake sequences is the gradient of the curve giving the cumulative frequency of occurrence versus magnitude ([10, 13]). The curves for the September 14, sequence, and for the entire period August 31 to October 1, are given in Figure 14. Data have been plotted in increments of magnitude of 0.2 and the shocks of magnitude above 3.0 have not been used. The points are linear between $M = 2.0$ and $M = 3.0$ and the slopes are $b = 0.84$ for the September 14 sequence and $b = 0.89$ for the two sequences together. The points between magnitudes 1.0 and 2.0 are also linearly distributed but with a different slope, $b = 0.36$. This value is very small and may point to the fact that the control over all shocks in this magnitude range was not as complete as expected, or that the relation between Log N and M is not the same for all magnitude ranges. The inclusion of the largest shock in the series and the sampling interval have, as was pointed out by Ryall et al. ([8]), a great influence in the determination of b. Including the largest shocks the author ([12]) found separately for the two sequences

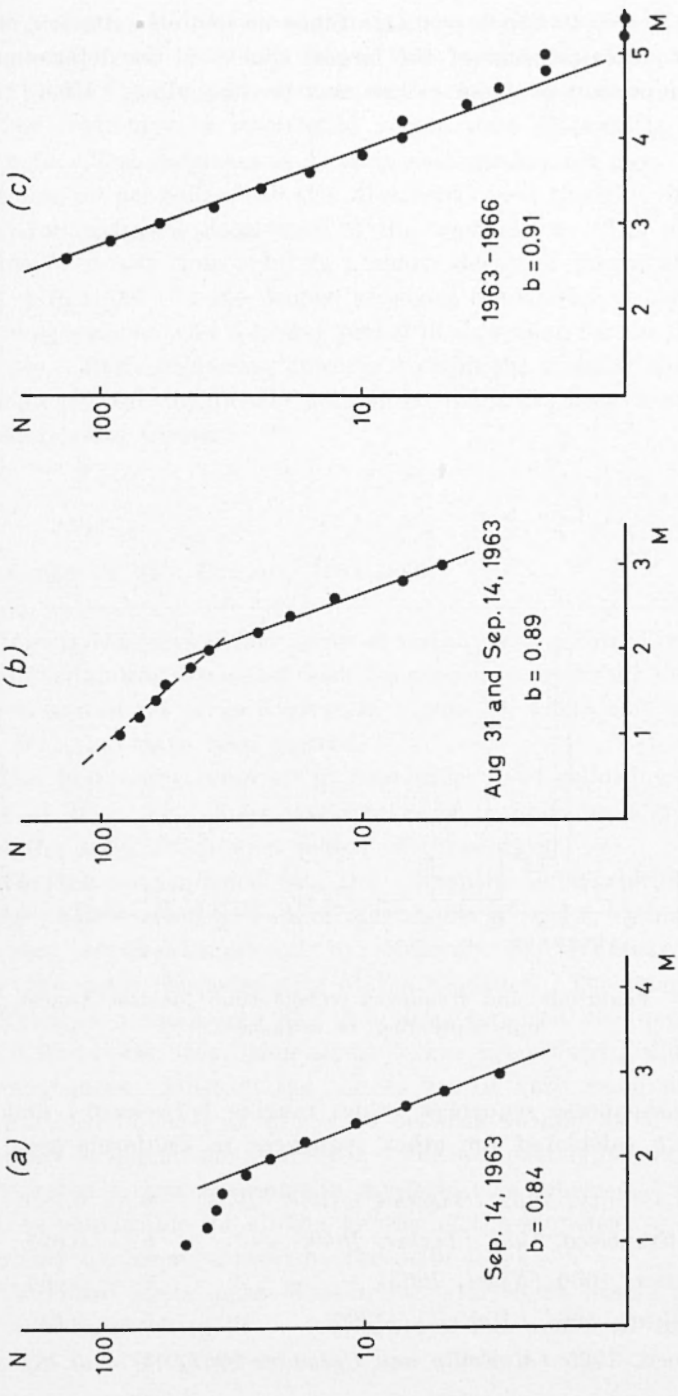

Fig. 14 – Cumulative frequency versus magnitude for the earthquakes of: (a) September 14, 1963 sequence. (b) August 31-October 1, 1963, interval. (c) period 1963-1966.

the values $b = 0.49$ and $b = 0.41$. Since no definite criterion is followed as to the inclusion of the largest shocks in the determination of b, a comparison of these values may be misleading. Utsu [13] has

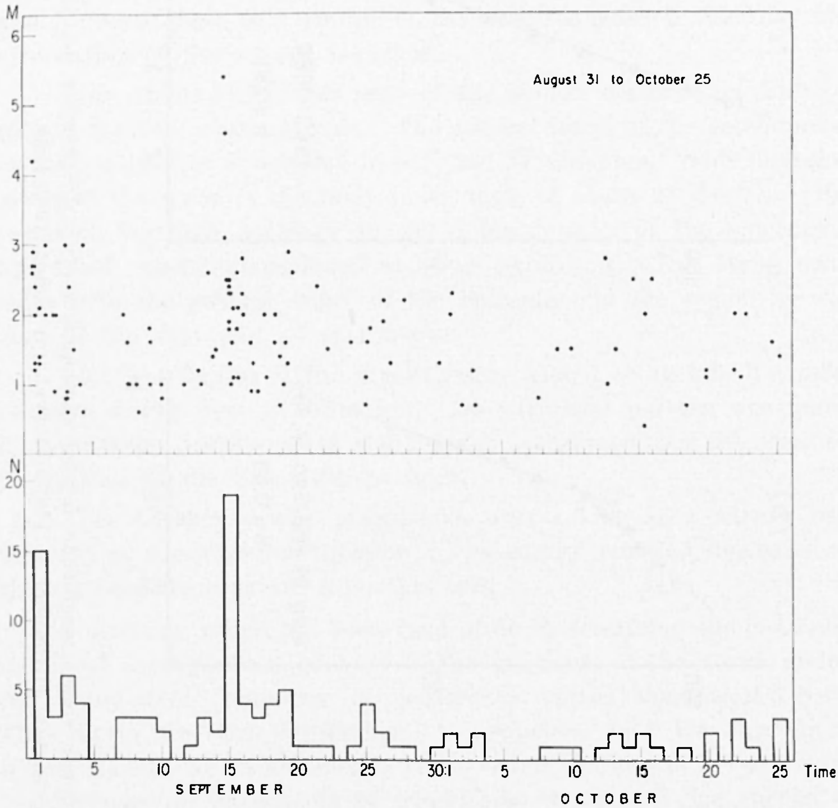

Fig. 15 – Magnitude and frequency versus time for the August 21 and September 14 sequences.

found for Japaneese sequences values ranging between 0.7 and 0.8. Values of b calculated for other sequences in California are:

Kern County, 1952 *(Oakeshot [editor], 1955)*	$b = 0.789$
San Francisco, 1957 *(Tocher, 1959)*	$b = 0.691$
Hollister, 1960 *(Niazi, 1963)*	$b = 0.664$
Corralitos, 1964 *(McEvilly, 1966)*	$b = 0.63$
Antioch, 1965 *(McEvilly and Casaday, 1967)*	$b = 0.78$.

Figure 14 also shows the frequency-magnitude relation for all earthquakes from 1963 to 1966 in this region, obtaining $b = 0.91$ which is the value usually found for Central California.

The frequency of occurrence versus time diagram is shown in Figure 15. The frequency is given in earthquakes per day. For both sequences, 36 per cent of all the aftershocks took place in the 24-hour period following the occurrence of the main shock. The plot of the magnitude versus time exhibits a sharp decay of magnitude of the shock with time. In the August sequence the shocks with magnitude 3.0 are spread out over a longer period of time than for the September sequence. Both sequences, however, exhibit the classical sharp decay of frequency and magnitude with time which has been found in earlier aftershocks studies.

Sequences of the Period, 1964-1966.

During this period four series of earthquakes occurred in the area. Data of the shocks associated with the sequences are given in Table V. The location of the series is given in Figure 16, where only the shocks with $M > 2.5$ have been plotted.

The first series occurred in September 1964 following an earthquake of $M = 3.8$. Four earthquakes of magnitudes above 2.5 followed the main shock in a period of three days.

The second sequence was the Corralitos series started on November 1, 1964 after a shock of magnitude $M = 5.0$. This sequence has been studied in detail by McEvilly ([5]). We take from his study the main characteristics of the sequence. The epicenters are all located in a small area of 4 km diameter, and the depths range from 9 to 14 km, this being about 7 km deeper than those of the 1963 sequences. Most of the shocks are of very small magnitude; of the 31 earthquakes of $M > 1.0$ between 16 and 24 of November only 6 are of magnitude above 2.0. The sequence represents a highly concentrated source, a volume in the form of a sphere of 1 km radius could be responsible for all the focuses of the sequence, and most of the energy has been released by the main shock.

The third series near Watsonville, started on January 1, 1965, with a main shock of $M = 3.5$ and was followed by 7 shocks with $M > 2.5$ in a 7 day period.

Table V – Series of earthquakes in the Watsonville area during the period 1964-1966.

Date	Origin Time	Latitude Nord	Longitude West	Magnitude M
Sept. 1 1964	$19^h49^m16.5^s$	36°52.2′	121 41.1	3.8
	19 52 06.3	52.6	40.4	2.6
	22 33 29.4	49.7	38.9	3.0
2	01 58 06.4	49.8	38.6	2.7
3	13 56 59.3	49.6	39.7	3.0
(Corralitos Series)				
Nov. 16 1964	02 46 41.7	37°03.3′	121 41.5′	5.0
	02 55 40.5	03.9	40.5	2.7
	05 09 13.6	03.8	40.3	2.5
19	20 47 40.1	02,3	42.1	3.2
23	09 05 08.0	02.4	42.9	3.5
Jan. 1 1965	09 56 51.3	36°50.5′	121°39.3′	3.5
	09 58 59.7	49.3	39.6	2.6
	10 47 36.5	51.5	37.8	2.7
	12 16 32.0	49.6	41.8	3.1
2	00 50 01.2	50.8	38.5	2.8
7	02 59 37.1	49.3	42.7	2.7
	03 00 03.9	50.6	37.7	2.9
(Sen Felipe lake series)				
Jan. 3 1966	15 38 38.6	36°58	121°28	2.2
5	05 55 06.4	59	28	2.9
9	00 03 20.6	58	28	2.5
	00 08 00.9	58	28	3.3
14	00 30 12.0	58	29	2.6
17	01 48 08.1	59	29	3.3
	02 03 20.0	59	29	4.1
	02 23 37.3	59	29	3.1
	02 48 37.6	37°00	28	3.0
	06 22 56.5	00	30	2.8
	10 36 17	00	30	2.6
19	15 04 48.8	36°58	27	2.4
	19 51 15.7	58	29	2.4
	20 02 34.3	58	29	2.7
21	04 10 36.0	59	28	3.5

The fourth sequence occurred on January 1966. The shocks are clustered in a small area near San Felipe lake. The spatial distribution of the sequence is then, of the same type as that of the Corralitos series, but they differ in the distribution of the magnitudes of the shocks with time. The largest shock, $M = 4.1$, occurred not at the beginning, but at the middle of the series. The sequence was started with an increase of seismic activity at the $M = 2.5$ level on January 3.

On January 17 occurred the main shock of the series, which was followed by 8 shocks of $M > 2.2$ in a 4 day period. Because of the concentrated location of the epicenters it is difficult to separate the first

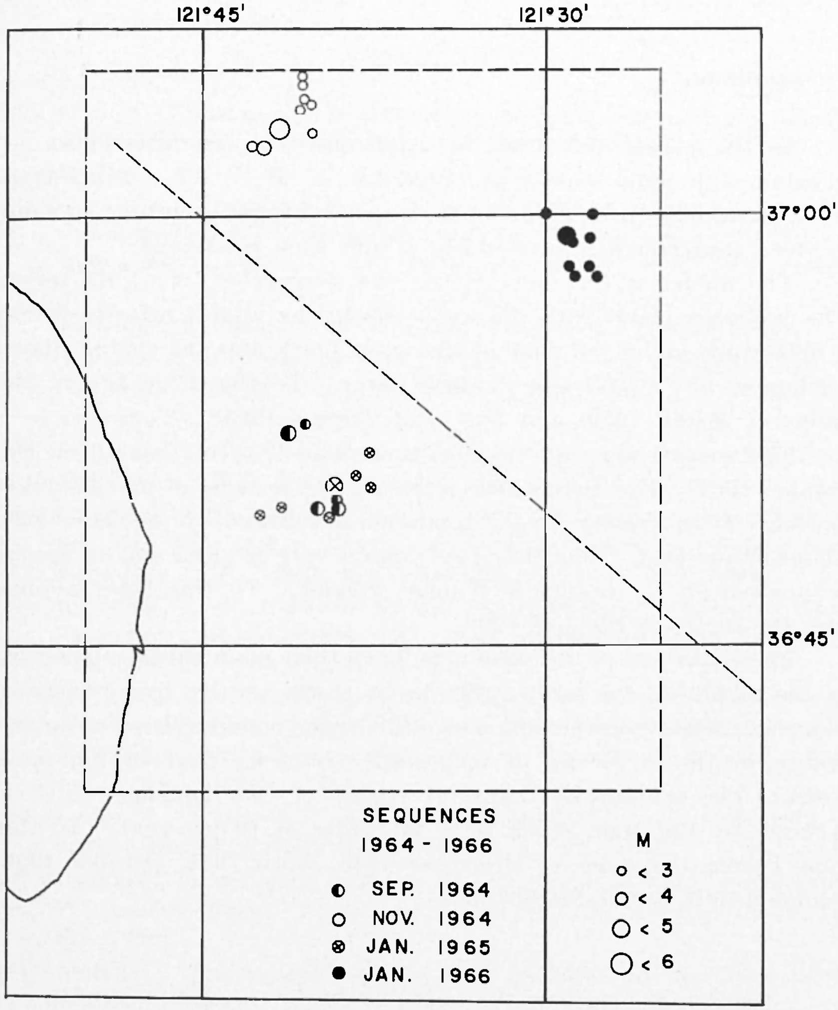

Fig. 16 – Epicenter location of the sequences of the period 1964-1966.

part of the activity from that following the main shock. In the Corralitos series the members of the sequence have small magnitudes compared with that of the main shock, so that the energy released by the main shock represents about 98 per cent of that of the total series. In the San Felipe, lake series the energy was released over a period of 18 days in small increments. The energy of the main shock represents only 72 per cent of the total.

Conclusions.

In the period 1953-1966 we have observed ten aftershocks sequences with main shocks in range $4.0 < M < 6.0$. Tentatively these series have been group in three general types according to some of their characteristics in the spatial and time behaviour.

The model of the first type is the September 14, 1963 series. The sequence starts with the main shock, the largest aftershock has a magnitude about 0.8 that of the main shock and the spatial distribution of the aftershocks in quite large. To this type belong the series of March 1959, and May and August 1963.

The second type groups sequences like that of Corralitos, November 1964. The main shock is followed by a series of much smaller shocks. It contributes to the total energy released by the series with about 98 per cent. The aftershock area is very reduced and all shocks originate from a considerably small volume. To this type belongs also the series of January 1960.

The sequences of the third type have their main shock somewhere at the middle of the series. The series starts usually by an increase of seismic activity in the area above the background level. The largest shocks in the series are of magnitude about 0.9 that of the main shock. The fraction of the total energy of the sequence which is released by the main shock is of the order of 70 per cent. To this type belong the series of December 1953, April 1954, October 1956, January 1961, and January 1966.

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REFERENCES

(1) Båth M., Richter C., *Mechanism of the aftershocks of Kern County, California earthquake of 1952.* " Bull. Seism. Soc. Am. ", **48**, 133-146, (1958).

(2) Bolt B. A., Turcotte F. T., *Computer locations of local earthquakes within the Berkeley Seismographic Network.* " Computers in the Mineral Industries ". Stanford Univ. Publ. Geol. Sci. **9**, 2, 561-576, (1963).

(3) Bunz V. I., *Methods for a detailed study of seismicity.* Ed. by Yu. V. Riznichenko. Jzdatel'stvo Akademii Nauk SSSR, Moskva (1960).

(4) Jennings C. W., Strand R. G., *Santa Cruz Sheet, Geologic Map of California.* Olaf P. Jenkins Edition; Calif. Division of Mines and Geology, 1 : 250,000, (1958).

(5) McEvilly T. V., *Earthquake sequence of Nov. 1964 near Corralitos, California.* " Bull. Seism. Soc. Am. ", **56**, 755-773, (1966).

(6) McEvilly T. V., *Parkfield earthquakes of June 27-29, 1966, Monterey and San Luis Obispo Counties, California: Preliminary seismic data, June-July 1966.* " Bull. Seism. Soc. Am. ", **56**, 967-971, (1966).

(7) McEvilly T. V., Casaday K. B., *The Earthquake Sequence of Sept. 1965, near Antioch, California.* " Bull. Seism. Soc. Am. ", **57**, 113-124, (1967).

(8) Ryall A., Van Wormer J. D., Austin E. Jones, *Triggering of Microearthquakes by Earth tides, and other features of the Truckee, California, earthquake sequence of September, 1966* "Bull. Seism. Soc. Am. ", **58**, 215-248, (1968).

(9) Suzuki Z., *A statistical study of the occurrence of small earthquakes.* I. Science Report. Tohoku Univ. Series 5, **5**, 177, (1935).

(10) Suzuki Z., *A statistical study of the occurrence of small earthquakes.* IV. Science Report, Tohoku Univ., Series 5, in "Geophys. ", **11**, 10-54, (1958).

(11) Tocher D., *Seismographic results from the 1957 San Francisco earthquakes.* California Division of Mines Special Report 57 (1959).

(12) Udías A., *A study of the aftershocks and focal mechanism of the Salinas-Watsonville earthquakes of August 31 and September 14, 1963.* " Bull. Seism. Soc. Am. ", **55**, 85-106, (1965).

(13) Utsu T., *Statistical study on the occurrence of aftershocks.* " Geophys. Mag. ", **30**, 521-605, (1960).