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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

ON THE DEVELOPMENT OF STRONG-MOTION INSTRUMENT NETWORKS IN THE UNITED STATES

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7. Author(s)
R.B. Matthiesen

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U.S. Geological Survey, Department of the Interior
345 Middlefield Road
Menlo Park, CA 94025

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A plan for the distribution of strong-motion instrumentation throughout the United States is outlined. The present national network of strong-motion instrumentation has evolved through the merger of several programs initiated by different agencies and organizations with objectives ranging from research to regulation. It is the result of the coordination of instrument maintainance and record keeping provided by the Seismic Engineering Branch of the U.S. Geological Survey. Concepts and strategies for planning and directing the development of the program include specific ground-motion and structural response studies. Certain regions in the United States are evaluated, in terms of activities and possibilities, in greater detail than in preliminary studies and make up the bulk of the report. They include the Northern, Central, and Southern California Coasts, Eastern California and Nevada, the Pacific Northwest, the Northern Rockies, Utah and Southeast Idaho, Colorado, New Mexico, Oklahoma, the Mississippi Valley, Ohio, the East Coast, Puerto Rico, Hawaii, and Alaska. The final section presents priorities and implications involved in the implementation of the program.

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ON THE DEVELOPMENT OF STRONG-MOTION INSTRUMENT NETWORKS IN THE UNITED STATES

by

R.B. Matthiesen

A Progress Report Submitted to
The National Science Foundation
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PREFACE

This report summarizes the concepts, possibilities, priorities, inferences, and afterthoughts that the author has muddled through while attempting to plan for and direct the development of the existing strong-motion instrumentation program. The report is not presented as a finished document, but only as a fleeting glimpse into the author's state of mind at one point in time. The author has not failed to change the report on each rereading, and he trusts that others will honor it with similar treatment.

The concepts in a report such as this are obviously a distillation of the author's experience while imbibing in the field of earthquake engineering. The comments and impressions transmitted to the author by many colleagues, cohorts, and collusionists have been blended in the mix-master of the author's mind and regurgitated. Many of these cronies will not recognize their contributions, and others may not like what has been done to their contributions.

R. B. Matthiesen

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FORETHOUGHTS

This report outlines a plan for the distribution of strong-motion instrumentation throughout the United States. The present "national" network of strong-motion instrumentation has evolved through the merger of several programs initiated by different agencies and organizations with objectives ranging from research to regulation. It is the result of the coordination of instrument maintenance and record archival currently provided by the Seismic Engineering Branch of the U.S. Geological Survey (formerly the Seismological Field Survey of the U.S. Coast & Geodetic Survey, or the National Ocean Survey, or the National Oceanic and Atmospheric Administration). The USGS operates the program under funding from the National Science Foundation (NSF) in cooperation with other federal, state, and local agencies.

NSF supports a data management function and the operation of a network of about 200 accelerographs and 300 seismoscopes utilized for studies of ground motion and building response. The State of California is developing its own strong-motion instrumentation program (CSMIP), which includes measurements of ground motion as well as the response of representative types of structures. The CSMIP network is the largest network operated by a single agency anywhere in the world. Eventually it will contain a total of about 1000 accelerographs. The Army Corps of Engineers (COE) is developing a program for monitoring the response of earth dams, which eventually will include as many as 400 instruments on over 100 dams. Other agencies and organizations are developing networks appropriate to their missions or objectives. At present the number of instruments owned by these other agencies is less than 100 in each case, although several agencies are still expanding their networks. The present distribution of accelerographs in the United States is indicated in Figure 1 (see: USGS, 1977, also).

In 1964 the cities of Los Angeles and Beverly Hills, California passed ordinances which required 3 accelerographs to be installed in all high-rise buildings. Initially, these instruments were installed and maintained as a part of the strong-motion program of the Seismological Field Survey (SFS). As the number of installations required by such codes increased, it became apparent that the maintenance of these instruments placed an inordinate burden on and created an imbalance in the SFS operated program (in 1972, 50 percent of the "national" program was concentrated in Los Angeles). With the transfer of the SFS program responsibility to the NSF and with the development of the CSMIP, the responsibility for maintenance of code required instruments has reverted to the city building officials and the building owners.

As the coordinated network of strong-motion instruments has grown, the maintenance of the instruments has required a larger staff than the USGS could provide under existing personnel ceilings. This situation has been resolved by the agencies with the larger networks performing their own installation and maintenance. The USGS maintains an archive of first class copies of all records, whereas other agencies maintain archives of their own records, only. In addition, the USGS coordinates the routine processing of all of the significant records, although other agencies will process their own data if they consider it to have a higher priority than does the USGS. In response to a recent change in their legislated charter, the CSMIP is beginning to develop a capability to process the data collected under that program.

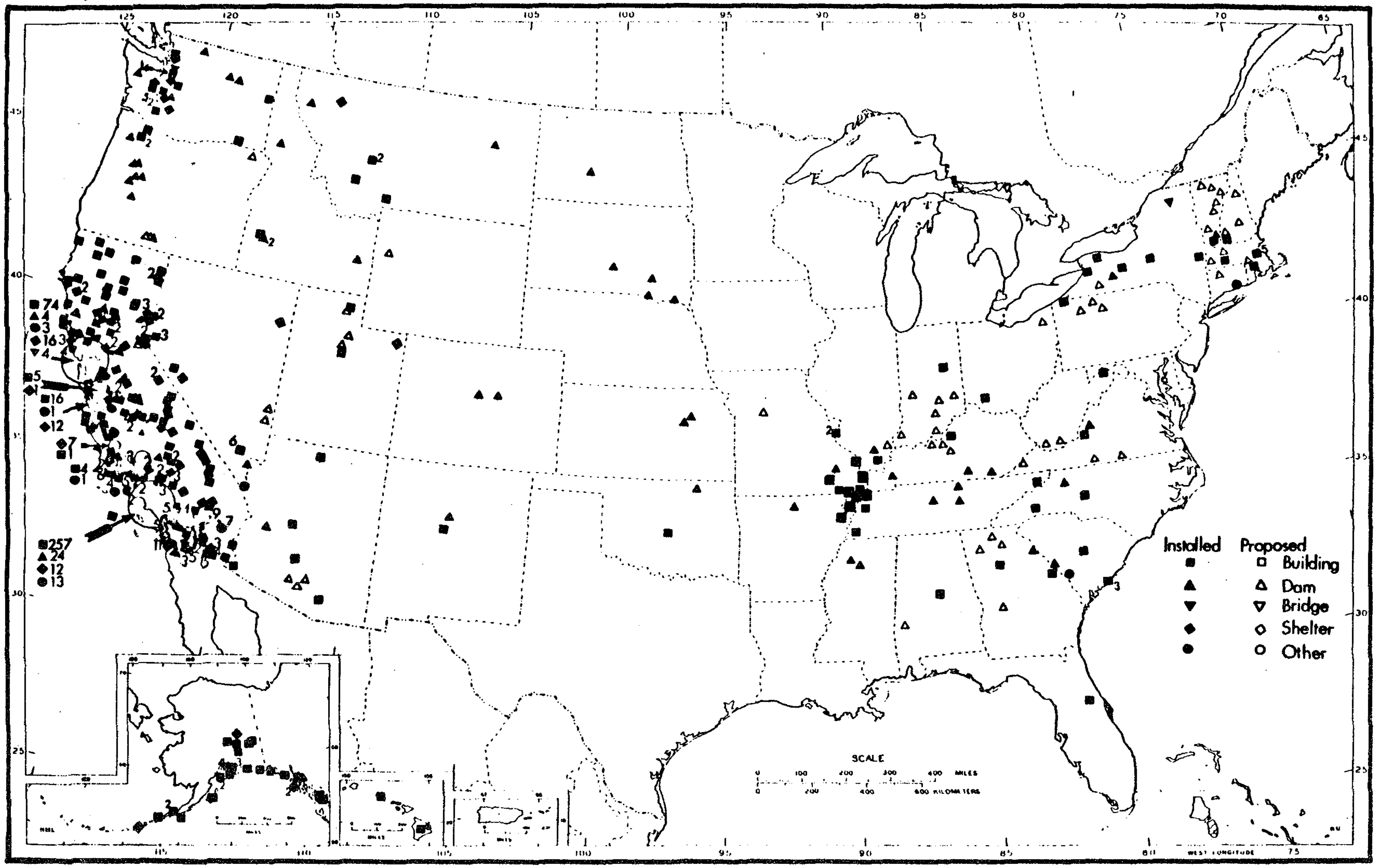

Fig. 1 - LOCATION OF STRONG-MOTION ACCELEROGRAPHS IN THE UNITED STATES, 1978

In 1976 a preliminary plan for improvement of the NSF supported network of strong-motion instrumentation was outlined based on 1) a preliminary evaluation of the occurrence of potentially damaging earthquakes in all parts of the United States, 2) an assessment of the types of research studies that would be appropriate to conduct in each region, and 3) a redistribution of instruments equal in number to those being maintained with NSF support. The initial concepts and criteria considered were 1) to plan arrays of accelerographs in the more active regions in order to obtain data which will permit the regional differences in attenuation of strong ground motions to be evaluated, 2) to plan arrays of accelerographs close to all potential sources of major earthquakes, and 3) to instrument representative types of structures (buildings, bridges, dams, towers, pipelines, underground structures, etc.) in all regions in which there exists a high probability that potentially damaging levels of motion will occur within the life of the structure.

The preliminary study affirmed the concept that plans must be formulated with respect to 1) regions where ground motions above some threshold level are recurring and 2) regions where major events occur but for which no return period can be defined. The former are regions in which studies can be planned with some confidence that low-amplitude data will be obtained and high-amplitude data may be possible. The latter are regions from which strong-motion data is desired, although it may not be obtained within the normal lifetime of an instrument; in such regions, some minimum level of instrumentation should be installed regardless of how long a period might occur before the next major event. The preliminary study of the recurrence of significant levels of ground motion was based on the numbers of events of Modified Mercalli Intensity (MMI) VI or greater that occurred within each 1/2 degree by 1/2 degree area in the U.S. during the period 1870 to 1970, as

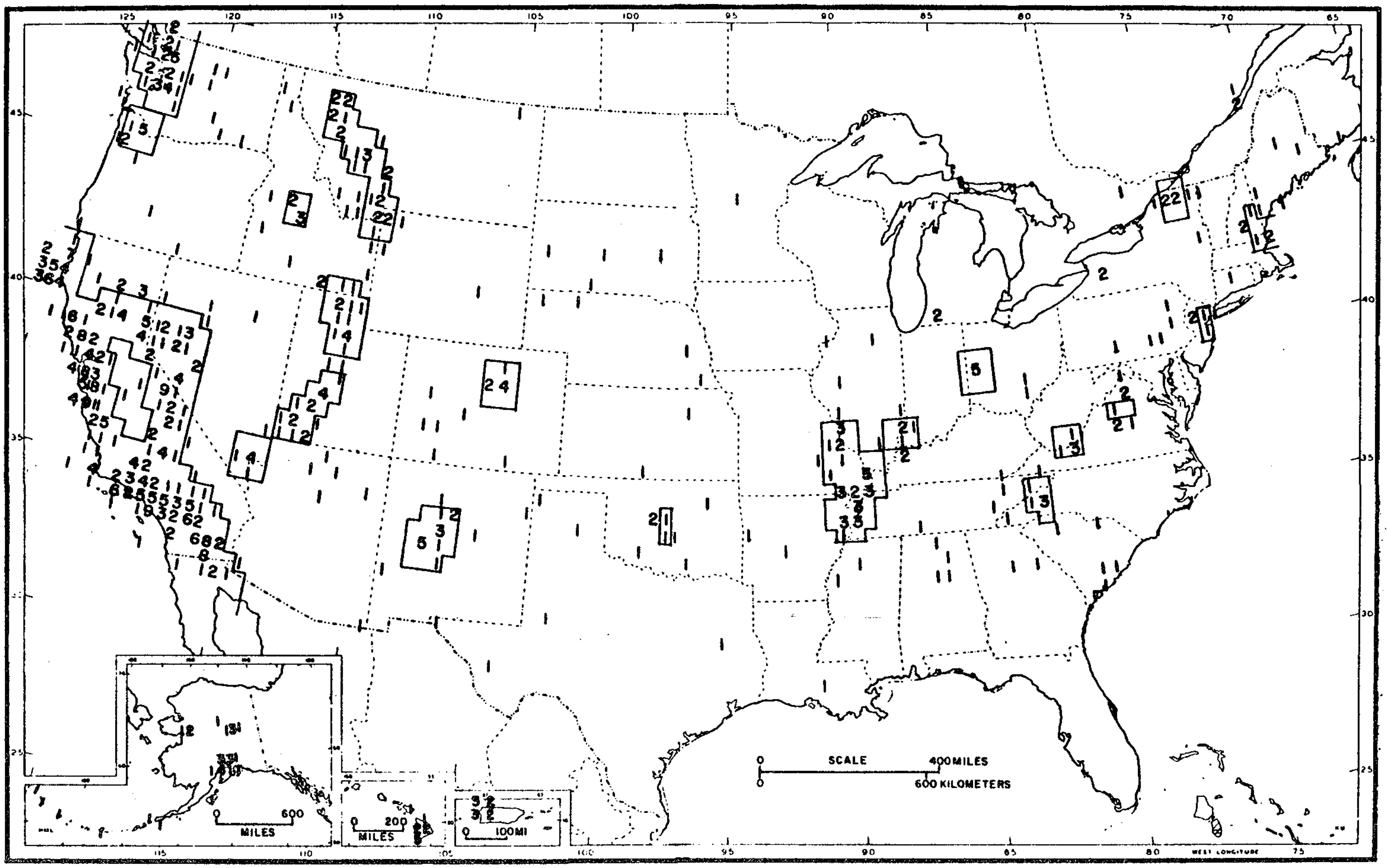

Fig. 2 - NUMBERS OF EVENTS OF MODIFIED MERCALLI INTENSITY VI OR GREATER, 1870 - 1970, AND REGIONS OF PROBABLE STRONG GROUND MOTION.

shown in Figure 2. The regions in which major events have occurred in the past are indicated by the map of all events of MMI = VIII or greater that have occurred in historical times shown in Figure 3.

The general features brought out by the preliminary study are well known since the data base is essentially the same as that used to develop seismic risk or hazard maps (Algermissen and Perkins, 1976, for example). There is a basic difference in approach between an evaluation of risk or hazard and one used to plan a strong-motion instrument network, however. In the former case, the maximum motion that has little likelihood of being exceeded in the life of a typical engineered facility is to be determined for each region. In the latter case, the likelihood that motion above some threshold level will occur within the lifetime of an instrument or a structure must be determined for a specific site.

Although all strong-motion studies are closely interrelated, they may be thought of as being separated into ground-motion studies and structural-response studies. A tentative assessment as to which types of studies could be conducted in each of the more active regions of the country was made in the preliminary planning study. Subsequently, cursory inspections were conducted in several areas to develop insight into the practicality of the tentative assessments. Reviews of the strong-motion activity in each of the active regions have been combined with the cursory inspections to revise the preliminary plan for a redistribution of the instruments and an assessment of which studies can be conducted in each region.

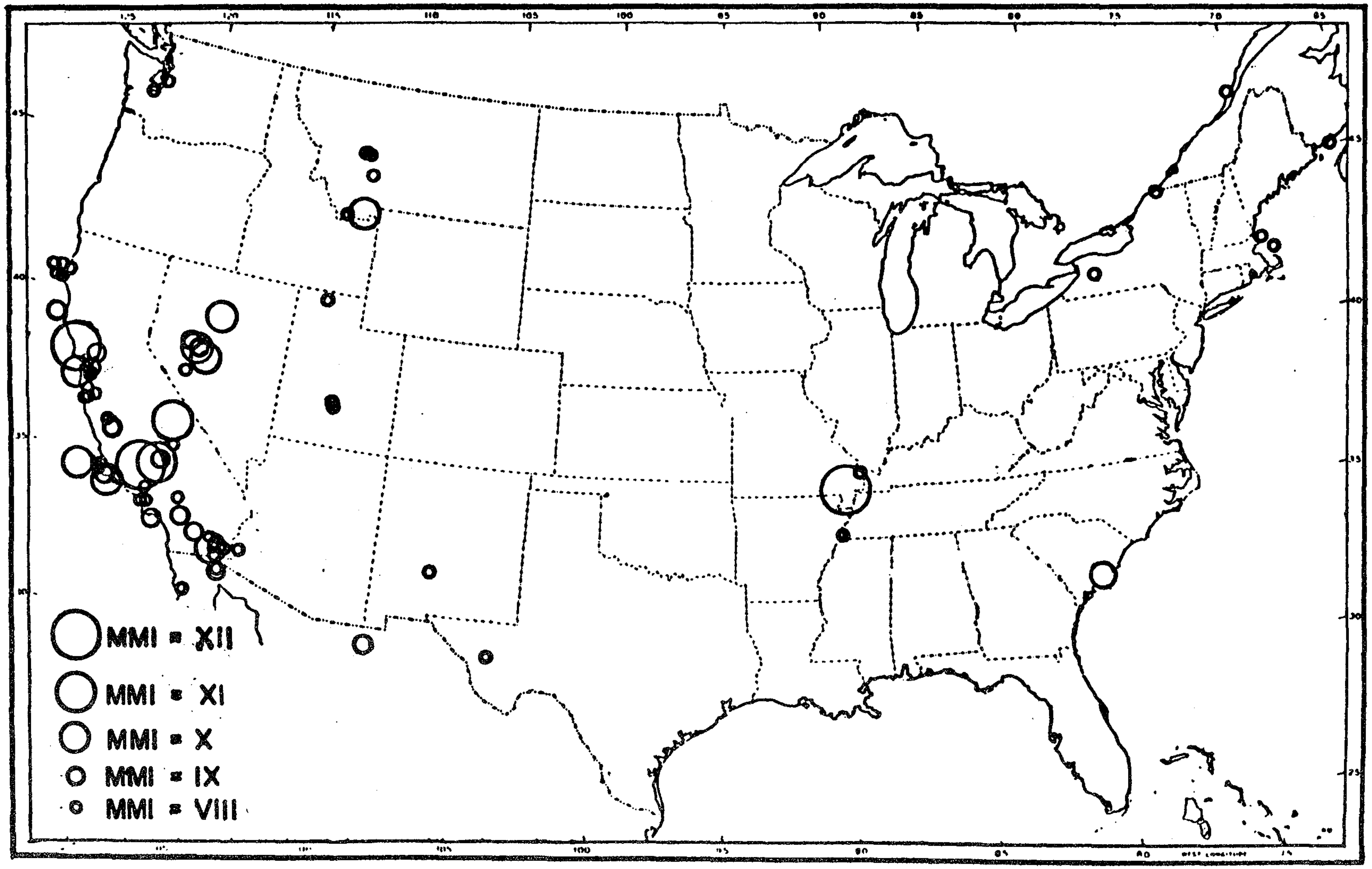

Fig. 3 - HISTORIC EVENTS OF MODIFIED MERCALLI INTENSITY VIII OR GREATER.

CONCEPTS AND STRATEGIES

The existing network of strong-motion instrumentation evolved from several programs that were subject to different constraints and objectives. Some were research projects directed toward understanding basic problems in earthquake engineering, whereas others were regulatory operations directed toward monitoring the response of critical facilities to provide measurements on which to base a decision regarding continued operation of the facility following a major earthquake. Between these extremes, there were a variety of research, planning, and operational programs for which strong-motion data were needed.

The fundamental purpose of the research that utilizes strong-motion data is to improve the mathematical models of the propagation of waves through the earth or of the response of structures to the resulting ground motions. Since in research studies the instruments can be placed wherever the desired data can be obtained most efficiently, the objectives of such studies generally can be accomplished with appropriately designed arrays located in the more active regions. Basic data for risk analyses and seismic zoning may be obtained from the placement of instruments at relatively widely-spaced intervals throughout the various seismic regions so as to obtain at least one record of strong ground motion from any potentially damaging event. This type of study can utilize the ground motion records obtained from instrumentation established to monitor the ground motions at various facilities. The amount of instrumentation required to monitor the response of a structure or facility is generally less than would be required for a research study of the same structure or facility, but the location of the instrumentation is obviously constrained to the specific structure or facility being monitored.

Special studies of ground motion and structural response that may require extensive instrumentation should be conducted in those regions where a short return period is reasonably certain or where the microearthquake activity suggests that a buildup to a major event is occurring; a minimum network of accelerographs for measuring ground motion should be located in all regions in which a relatively long return period is indicated; individual accelerographs should be located where strong ground motions could have been recorded in the past but where no return period can be established; and seismoscopes may be used to provide a "background" level of instrumentation in all areas where there is little likelihood of an event being recorded in the near future (the lifetime of an accelerograph, 20-30 years). In addition to these permanent installations, provision should be made for the rapid deployment of instruments in areas in which there appears to be a buildup of activity leading to a major event or in the epicentral area for aftershock studies when a major event occurs. Furthermore, the development of a permanent network of strong-motion instruments, the rapid deployment of instruments to areas where there is a buildup of activity, and the proper interpretation of the results depend on the existence of adequate instrumentation for recording microearthquake activity and determining the locations of the events recorded.

Ground Motion Arrays

For engineering purposes, the ground motion studies for which strong-motion records are desired may be classified as follows:

- Studies of the spectral characteristics of strong ground motion and of the variations of these characteristics with the nature of source, the travel path or regional geology, and the local site conditions,

- o Studies of the variations in strong ground motions over distances of the order of a characteristic dimension of representative structures or systems,
- o Studies of soil failures such as liquefaction or landslides.

In the first two types of studies, records of ground motions are desired over as wide a range of source strengths, distances, and site conditions as possible. For the lower ranges of source strength, much of this data can be obtained from measurements made during aftershocks. In this case, one of the greatest uncertainties in the planning of strong-motion arrays is eliminated since the location of the array is constrained by the epicentral location and size of the main event. The more important data for engineering purposes comes from the potentially damaging motions close to the sources of major earthquakes (Mag. = 7.5 or greater). Since this information can be obtained only from instruments that have been installed prior to such events, arrays must be installed in those regions where major events are likely to occur. For studies of soil failure, the most important data can be obtained only during the main shock, since the phenomena being studied occur then and probably will not recur during aftershocks which are typically of lower amplitude.

Small but potentially damaging earthquakes (Mag. = 5.5 to 6.0) may be modelled as generating a simple displacement pulse from a point source. For example, an analysis of one component of the ground motion measured close to the source of the Parkfield earthquake of June, 1966 is shown in Figure 4 (Caltech, 1973). A major part of this motion is clearly the result of a simple displacement pulse. At the present time, the locations of such small sources cannot be predicted adequately, except in a statistical sense. Large earthquakes (Mag. = 7.0 to 8.5) may be modelled as generating multiple displacement pulses from line or plane sources of considerable extent whose

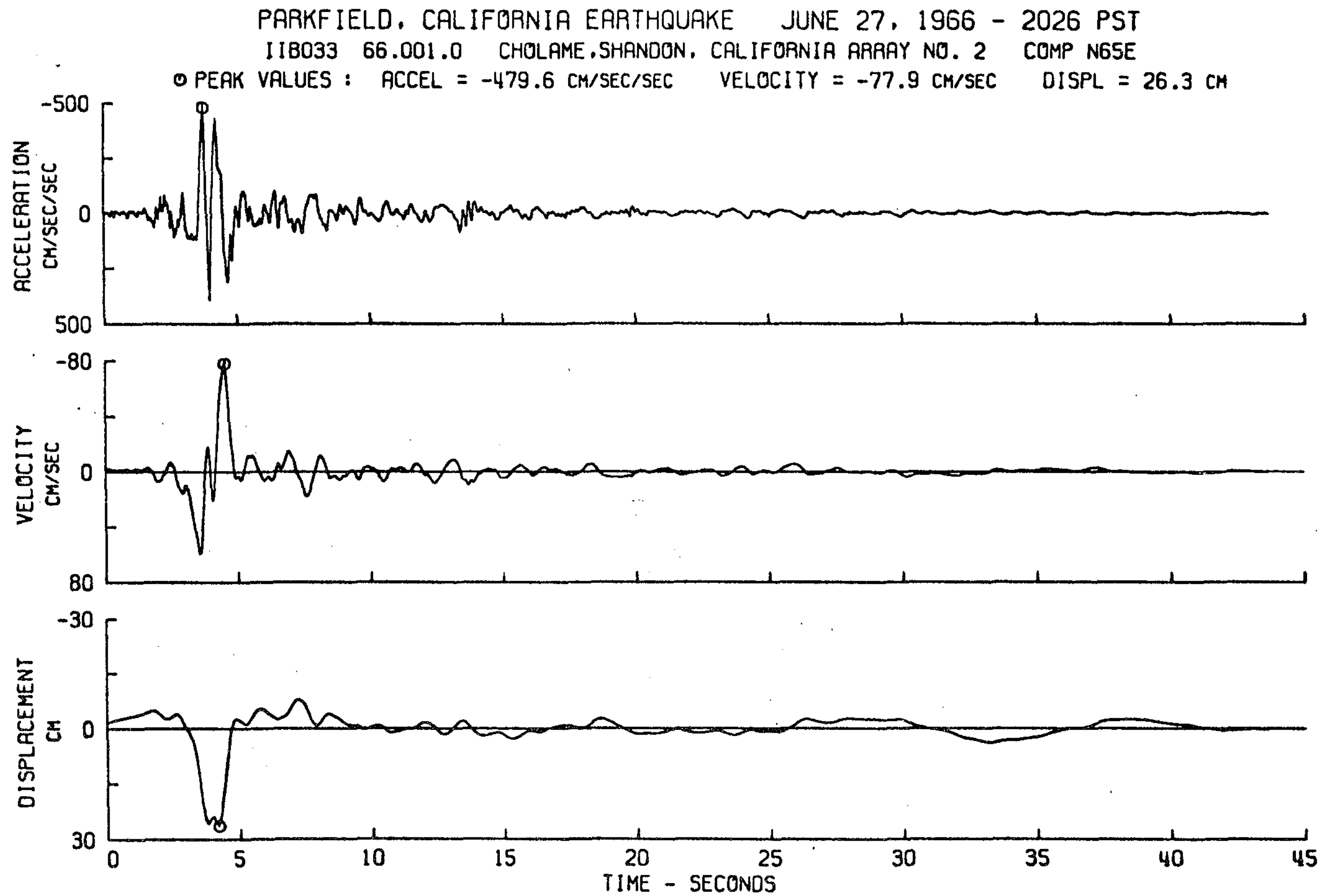

Fig. 4 - ACCELERATION, VELOCITY, & DISPLACEMENT TRACES FOR THE N65E COMPONENT OF MOTION AT CHOLAME-SHANDON STATION 2, PARKFIELD EARTHQUAKE, JUNE 27, 1966.

probable locations can be predicted but which occur too infrequently to insure a good return of data.

The inhomogeneity of the materials through which the earthquake motions are propagated leads to a considerable amount of scatter in the data. As a result, a greater amount of instrumentation is required than would be necessary otherwise. For example, a simple empirical interpretation used extensively at the present time is to assume that some parameter (such as the peak acceleration) will attenuate in a well-defined manner with distance. That this is not the case is illustrated by Figure 5, wherein data from the 1971 San Fernando earthquake has been plotted. The simple interpretation of the data assumes that it should define a straight line on this log-log plot, whereas the amplitudes differ by an order of magnitude at any given distance. Refinements in the interpretation of the data can reduce this scatter somewhat, but the design of arrays to study ground motion would be insufficient without provision for a considerable redundancy so that a measure of the scatter in the data can be determined and so that more refined interpretations may be made.

One question to be resolved by studies of ground motion concerns the influence of the near-surface soil layers on the amplitude of the surface motion and the nature of the variation of motion with depth. Simple theories have been advanced to show that surficial layering can amplify the motions at frequencies that correspond to harmonics of the natural frequency of the layers, or it can attenuate motions as a result of internal energy absorption within the layer. This is illustrated in Figure 6, in which theoretical results for a single layer over a half-space are shown. The regular spacing of the peaks corresponds to the harmonics of the natural frequency of the layer, wheareas the diminution of the amplitude of the peaks at higher frequencies results from the internal energy absorbtion that was

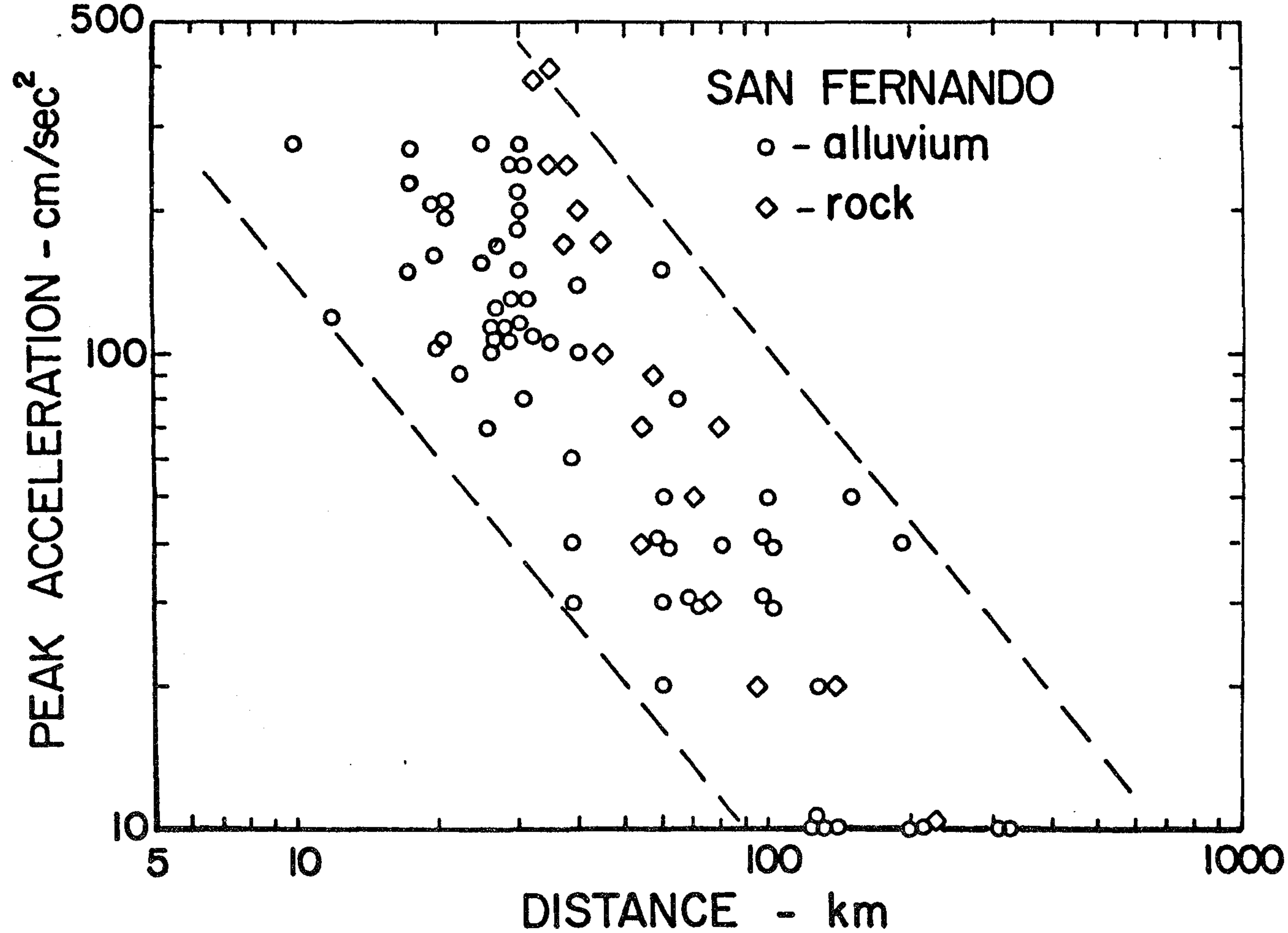

Fig. 5 - ATTENUATION OF PEAK ACCELERATION WITH DISTANCE, SAN FERNANDO EARTHQUAKE FEBRUARY 9, 1971.

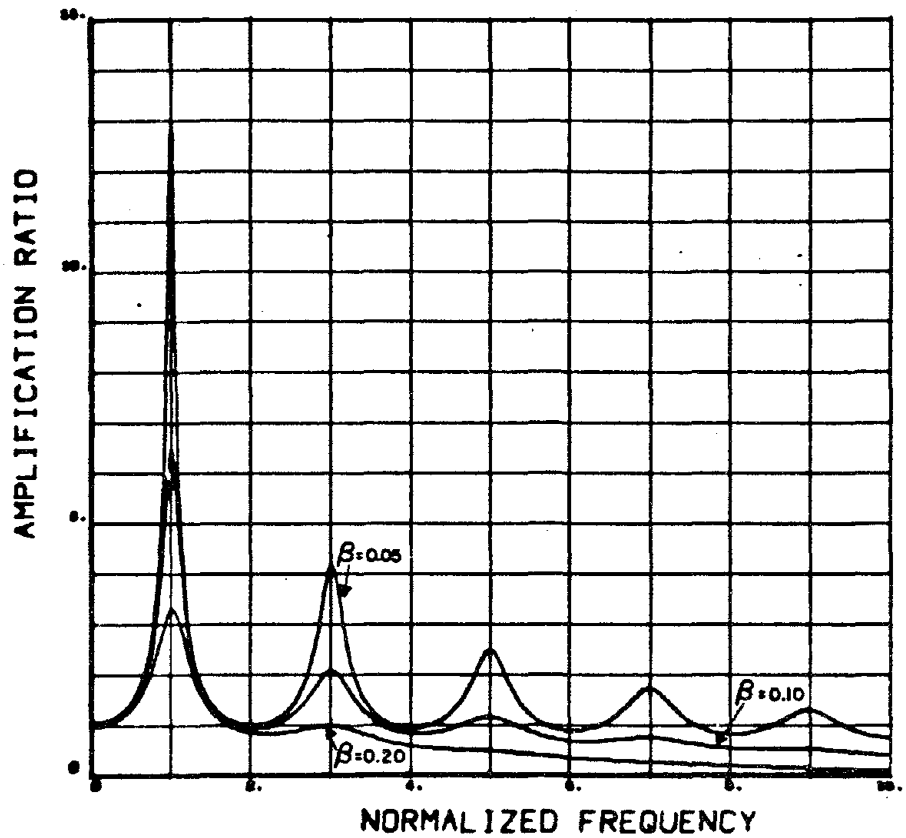

Fig. 6 - AMPLIFICATION SPECTRA FOR A UNIFORM LAYER OVER ROCK. (from: DOBRY, WHITMAN, AND ROESSET, 1971)

assumed for the material in the layer. In the data available from strong-motion records, there are few spectra that exhibit these simple characteristics. One such spectrum is shown in Figure 7, wherein the spacing of the peaks at longer periods suggests that the site could be modeled as a single soil layer over rock. At periods less than 1.0, other effects begin to predominate, and at a period of 0.4 sec., a bulge in the spectrum requires that some other feature be introduced into the model (a second layer, a characteristic of the source, etc.). The actual layering at this site has not been determined. This example illustrates that simple models of the site cannot be expected to explain all aspects of the ground motion or the resulting spectra but that a considerable amount of modelling can be based on data from surface instruments. Detailed site investigations should be conducted when significant records are obtained.

The constraints imposed on array design as a result of the scatter in the data, the inability to predict the specific locations for small but damaging events on active faults, and the extent of the sources of large events suggest that the most appropriate type of permanent array for ground motion studies may be a grid of surface instruments aligned with a known fault. A grid of instrument stations can be designed to cover that portion of a fault in which small events are likely to occur or to cover selected areas along the length of a fault for major events. The grid-type array allows for the uncertainty in the location of the small events, and it provides for the redundancy required by the expected scatter in the results. Results obtained from such arrays can be interpreted in terms of the simple empirical relations currently in vogue; they permit more sophisticated wave-propagation models to be developed; they can be "inverted" to yield models of the subsurface geological structure; or they can provide insight into source

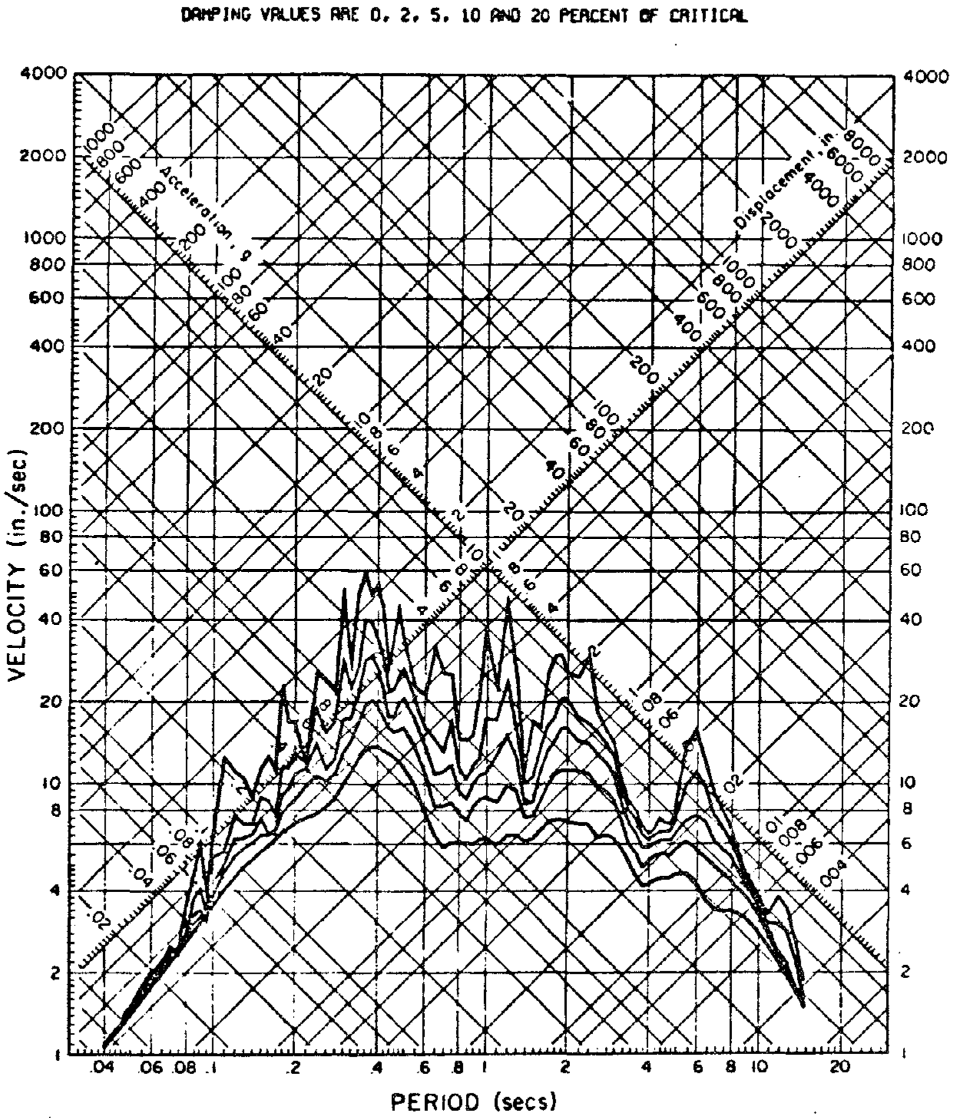

Fig. 7 - RESPONSE SPECTRUM FOR THE N85E COMPONENT OF MOTION AT CHOLAME-SHANDON STATION 5, PARKFIELD EARTHQUAKE OF JUNE 27, 1966.

mechanisms.

In addition to a decision concerning the location of the arrays, a primary decision to be made concerns the spacing of the grid. The finer the grid spacing, the more detailed are the interpretations that are possible, but the higher the cost of the instruments and their maintenance. For events of magnitude 6 or greater in areas with relatively simple near-surface geology, an array of instruments with a grid spacing of about 20 km may provide sufficient data to define a simple attenuation relation between a peak parameter and distance as well as a measure of the scatter in the data. For more refined interpretations, a grid spacing as large as 20 km would limit the amount of detail that could be included in the model and would be unsuitable if the regional geology varies significantly over short distances. Variable grid spacings are probably desirable, depending on the complexity of the surficial geology of the region and the nature of the desired study.

Downhole strings of instruments have been suggested in order to obtain data on the three-dimensional nature of strong ground motion. The simplest concept for design of such "downhole" installations is to select a site where there is a significant contrast in shear-wave velocity between the "basement" rock and the overburden in a relatively shallow (h = 100 m, or less) surface layer and to place downhole triaxial-transducer packages in the rock, within the layer, and at the surface. A complete interpretation of the data may require at least three such strings of downhole transducers in close proximity in order to observe wave fronts, etc. On the other hand, most of the information desired might be obtained from a sufficiently dense grid of instruments at the surface and a complete analysis of the data in terms of wave propagation theory. If a downhole array is contemplated, special studies should be conducted to design the array and to justify its installation because of the significantly greater initial expense.

In many regions of the country in which major earthquakes have occurred within historic times or where geologic evidence portends major earthquakes in the future, the rate of return of strong-motion data above the minimum level deemed to be significant is not sufficient to justify an extensive array of instruments. Still, to provide quantifiable data for correlation with damage studies, it is desirable to obtain at least one record of ground motion from any potentially damaging earthquake (Mag. = 6, or greater). In the initial development of the CSMIP such a criterion was adopted. This required that accelerographs be placed at a maximum spacing of 80 to 100 km in all regions of the state in which such events may occur. Even in California, the justification for such instrumentation cannot be based on an expected rate of return of data but must be based on the importance of obtaining the data for correlation with observed damage if such an earthquake should occur.

Structural Response Arrays

The structural response studies of interest may be classified as follows:

- Studies that can lead to improved models of structural response in the range between the initiation of damage and total failure or collapse.
- Studies of the influence of the supporting soil on this response.

Representative types of structures include engineered embankments and retaining systems as well as buildings, bridges, dams, etc.

The inelastic response of structures is relied upon to prevent total failure or collapse of buildings during earthquakes (SEAOC, 1975). Because of the paucity of measured response from buildings that have experienced some structural damage, however, the inelastic response of structures is the least understood range of response of actual buildings. Experiments to study response in the range somewhat beyond the initiation of damage can be conducted on shake tables, but the influence of "nonstructural" elements or soil-structure interaction is difficult to include in such experiments. On the other hand, data from recent earthquakes indicates that current design practice does not necessarily provide adequate inelastic deformation capacity to prevent collapse (NOAA, 1973) and that soil-structure interaction may increase the effective damping during earthquakes (Hart, 1975). Data on structural response in the range of interest is not likely to be obtained during aftershocks, since the response during aftershocks is not likely to cause damage to structures that were not damaged by the main shock. Thus, permanent installations of instruments to measure the response of representative types of structures must be made in regions in which potentially damaging motions are likely to occur in the near future.

An important factor that can be evaluated from the response of structures during an earthquake is the level of response at which structural damage is initiated. This factor is not easily estimated from analytical studies alone. Analyses of records obtained from instrumented buildings during the 1971 San Fernando earthquake provide some insight in this regard. The response of nine of the instrumented buildings has been studied in some detail, and several others were subjected to simplified analyses (Blume and Assoc, 1973; Gates, 1973; and Matthiesen, 1971). The instrumented buildings represent "typical" design practice under provisions of the 1960 and 1966 City of Los Angeles building codes. As an indication of the level of response that corresponds to the initiation of structural damage, a comparison of the maximum base shear that the instrumented buildings experienced during the earthquake to that for which they were designed is summarized in Table 1 along with observations of the extent of damage. These results indicate that during the earthquake, structural damage did not initiate until the base shear was at least three times the design base shear. This observation provides a measure of what the engineering design profession (or at least the engineer who designed each building) implicitly assumed as the level of motion that distinguishes "moderate" levels of ground motion from "major" levels of ground motion. This level of motion is dependent on the design coefficient and the structural detailing practice used. Consequently, it is time dependent (building codes change), personality dependent (design practice varies from one individual or office to another), and spatially dependent (building codes and design practice vary with location).

In the range between initiation of damage and total failure or collapse, modal response concepts are not strictly applicable, although they are the basis for most interpretations of records of the earthquake response of structures. The concepts used in the planning of arrays of instruments for studies in this range should be related to the potential failure mechanisms of the structures. For buildings, the objective is to study the nature of the change from essentially modal but nonlinear response to non-modal and inelastic response approaching collapse. Figure 8 shows the records from a 12-story building that experienced a small excursion into the damaging range during the 1971 San Fernando earthquake. Two features of building response that are apparent in the records from that earthquake are illustrated in this figure: 1) early in the record the building responded in its higher modes, whereas later in the record it responded in the fundamental mode; and 2) as

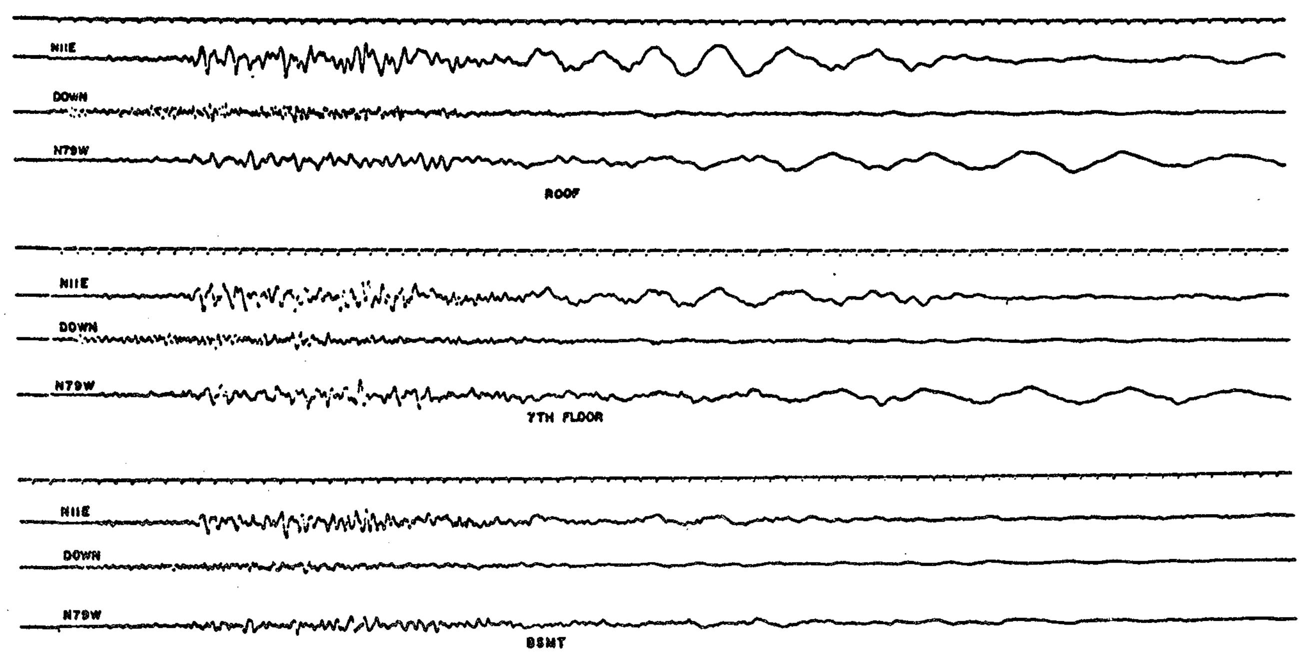

Fig. 8 - ACCELEROGRAPH RECORDS FROM 15250 VENTURA BLVD., SAN FERNANDO EARTHQUAKE FEBRUARY 9, 1971.

Table 1 - Building Performance in 1971 Earthquake

Building	V_e / V_d	Remarks
Bank of California 14250 Ventura Blvd	4.0	$ 44,000 total damage 12,000 structural damage
Holiday Inn 8244 Orion Ave	3.5	$145,000 total damage 2,000 structural damage
Holiday Inn 1640 Marengo St.	3.0	$ 95,000 total damage 2,500 structural damage
Bunker Hill Tower 800 W. First St.	2.9	no damage
Muir Medical Center 7080 Hollywood Blvd	2.5	$ 2,000 total damage no structural damage
Northrup Building 1800 Century Park East	2.5	no report of damage
Water and Power Building 111 No. Hope St.	2.5	no report of damage
KB Valley Center 15910 Ventura Blvd	2.3	$ 3,000 total damage no structural damage
USC Medical Center 2011 Zonal Av.	2.3	no report of damage
Certified Life Building 14724 Ventura Blvd	2.1	$ 32,000 total damage no structural damage
Kajima Building 250 E. First St.	2.0	$ 1,000 total damage no structural damage
University Graduate Center 3440 University St.	2.0	no report of damage
Sheraton Universal 3838 Lankershim Blvd	1.7	$ 2,500 total damage no structural damage
Beneficial Plaza Bldg 3710 Wilshire Blvd.	1.7	no report of damage
Airport Marina Tower 8639 Lincoln Blvd.	1.4	no report of damage
Mutual Building 3407 W. Sixth St.	1.2	no report of damage

the fundamental mode response increased, a point was reached where the fundamental period lengthened significantly. The latter is interpreted as corresponding to the initiation of structural damage in this building (Matthiesen, 1971, and Blume and Assoc., 1973). Since there was only a slight excursion into the damaging range, the subsequent response appears to be modal in character with diminishing amplitude. Unfortunately, with instruments only at the seventh floor and roof, it is not possible to make a detailed study of the changes in "mode" shape that must have accompanied this change in period of vibration. Although such a study is of secondary value when monitoring the response to observe if significant damage may have occurred, it is of primary importance in research into structural behavior in this range (Blume and Assoc., 1973 and Gates, 1973). For this purpose, it is desirable that several representative types of structures in active areas be instrumented with an extensive number of instruments so that an interpretation of the change in behavior in the range beyond the initiation of damage will be possible. Because of the cost of the extensive instrumentation that will be required, such installations must be located in sufficiently active regions so that an adequate return of data will be achieved.

The minimum requirements for instrumentation in buildings have been outlined by Rojahn and Matthiesen (1977). A basic pattern of instrumentation that would permit an adequate interpretation of the lateral and torsional response is recommended, and additional instrumentation, which would be desirable depending on other effects that might be studied in a particular situation (soil-structure interaction, vertical motion, etc.), is outlined. Similar general concepts have been prepared for the instrumentation of bridges (Raggett and Rojahn, 1978). In this case, however, the modal response is of somewhat less importance than are concepts based on the effects of expansion joints and interaction between different segments of the bridge or between the bridge and the abutments or embankments. Concepts for the design of arrays to study the response of dams, power plants, underground structures, etc. need to be developed. In an earthquake, a large earthfill dam responds as a three-dimensional solid constrained along its base and abutments by the supporting materials, which may be rock or alluvium. The dam will exhibit modal response characteristics, with the modes having closely spaced frequencies and complex shapes. For earthfill dams the failure mechanism is anticipated to be through embankment slumping along a slip surface, and a critical measurement may be one at the toe of the slip surface or at a "representative" point within the slumping material. In addition, a measurement of the pore water pressure within the slumping material could be important in the analysis and interpretation of the response. The purpose of such instrumentation is to permit the initiation and progression of the failure to be identified, and this may bear little relationship to the modal response of the dam. In power plants, the critical response may be that of major pieces of equipment, such as pumps or steam generators, rather than that of the support structure.

Failure analyses should be conducted for each type of structure that is to be instrumented. These should be evaluated relative to the type of instrumentation and specific instrument locations required to identify how failure initiates.

Costs and Benefits

An evaluation of the probability of results being obtained in the near future (the lifetime of the structure) can be combined with an evaluation of the cost of the required instrumentation and its installation to determine if the benefit to be derived justifies the expected cost based on whether the purpose of the instrumentation is research or operations. Under the procedures that have been used in the recent past, the cost of maintenance has been about three times that of the instruments themselves (depreciated over a 20-year life). As a result, the procedures used in instrument maintenance, in particular the service interval, have a critical impact on any attempt to optimize the network design. The results of a study of the effect of the length of the service interval on instrument performance that lengthening of the service interval from three to six months would decrease the level of record recovery from about 90 percent to 85 percent, but other changes could be introduced into the instrument maintenance operations to increase the reliability of the instruments and the level of record recovery. The data from which the study was made need to be updated once the entire network has been brought up to the desired standards of operation.

At the present time (1978), the average cost of instrument maintenance throughout the U.S. is about $450 per instrument per year. This average cost obviously does not apply to each instrument, which may be a part of a closely spaced array or may be located at an isolated site. For example, the cost for maintenance of a typical station in Alaska, or of any station which is remote from other stations, will be two to three times this average cost, whereas the cost of maintaining one additional instrument at a dam (where there are several other instruments) or the cost of maintaining the instruments in one additional building (in an area where there are already several other instrument stations) will be less than this average cost. On the other hand, the maintenance operations and instrument reliability are being upgraded constantly, so that any assessment of costs other than as an average cost of the total operation for an entire year is probably not too meaningful.

In those areas where the temporal distribution of events appears to define a recurrence relationship, the cost of instrument maintenance plus the yearly depreciation of initial instrument costs can be multiplied by the return period to establish the cost per record at each site. This cost has been found to vary from $1,200 per record in the Cape Mendocino area to over $10,000 per record in the Transverse Ranges (Matthiesen, 1976). It will be significantly higher in less active areas.

The cost of data management is not easily related to any specific feature of the size of the network, although it might be related to the total number of instruments or to the number of instruments in areas of current activity. A certain minimum level of staff and equipment for data processing are required if the data is to be processed efficiently immediately following a major earthquake. At present, the cost of data processing averages about the same as the cost of instrument maintenance when considered on an annual basis (that is, the total cost of data managment and the total cost of instrument maintenance are about the same). If the network is expanded, however, the cost of data management would probably decrease relative to the cost of instrument maintenance.

The value of each record depends on the objective of the program for which the data is to be obtained. For example, in the programs that monitor the response of large dams, the value of the records may depend on the economic loss which would occur if the reservoir had to be drained to permit a thorough inspection of the dam rather than on any parameter related to the size of the dam or the potential for improvement in dam design. On the other hand, the value of a set of records to be used in a research study depends on the ultimate use of the results which may be in design studies or in the development of regulations. These benefits are not easily forecast. Obviously, the first set of data that will yield answers to some of the unanswered questions related to the nature of strong ground motions close to a magnitude 8 earthquake or from earthquakes in the central part of the country will be of considerable value for hazard analyses or design studies, whereas a single record with an amplitude of about 0.05 g which is obtained at any of the sites in California will be of little benefit by itself.

ACTIVITIES AND POSSIBILITIES

The "strong-motion activity" of each of the regions of relatively high seismic activity must be evaluated in greater detail than was done in the preliminary study. In addition, the implications of the history of major faulting in each region should be considered (Allen, 1975), but this has not been a major factor in the present study. The data set used in this evaluation of the seismic activity was the compilation by Coffman and von Hake (1973). This is believed to be a reasonably consistent set for most of the country for the period from 1870 to 1970. Prior to 1870, the "history" in the west is not complete, but the more recent history is thought to be the more significant for use in a planning study of this type (McGuire, 1977). The previously used criterion of considering intensities of MMI = VI or greater has been followed since lower intensities are believed to be associated with ground motions below the threshold of significant strong ground motion (a peak ground acceleration of about 0.05 g). A strong-motion accelerograph will record high accelerations from smaller events but only if the instrument is near the source.

For each of the regions of high activity (see Figure 2), maps are presented, and the MMI = VI isoseismal contour for each event in the region is approximated as a circle (or sausage) drawn around the epicenter (or the fault break). The radii of the circles are related to the epicentral intensities (MMI_0) as indicated by the following table:

MMI_0 =	VI	VII	VIII	IX	X	XI	XII
r, km =	10	20	40	80	160	175*	175*

* Extended along the fault zone, if known.

The values in this table are estimates based on a casual perusal of papers by

Wiggins (1964), Evernden and Ack (1976), and some unpublished preliminary work by Rojahn (personal comm., 1977). The tabulated values were used for sites west of longitude 105 degrees, whereas an arbitrary factor of 3 was used to represent the lower attenuation in the east compared to that in the west (Gupta and Nuttli, 1976).

The circles approximating events located offshore or out of the country have been drawn with radii consistent with the onshore or "domestic" intensities listed by Coffman and von Hake. The areas in which several strong-motion records could have been obtained are indicated by the overlapping of the circles approximating the MMI = VI contours. The number of events that would have caused significant ground motions at a particular site can be determined by counting the number of times that the site is encircled by the MMI = VI contours. By identifying the associated events, a history of possible strong-motion recording at any specific site may be projected, and the cummulative number of events versus the date of the projected recording may be plotted. If the concept of "recurrence" of ground motion has meaning, such plots should indicate a linear relation between the number of events and the date of occurrence.

The results obtained using this approach are not expected to be "elegant"; they could be made to appear to be more precise; but they are believed to be adequate to provide the insight necessary to permit rational plans for strong-motion networks to be developed.

Northern California Coast

The well-known concentration of activity near Cape Mendocino on the northern California coast is illustrated in Figure 9. This is at the northern end of the San Andreas fault at its junction with the Mendocino escarpment.. Only in the area from Orick to Petrolia would it have been

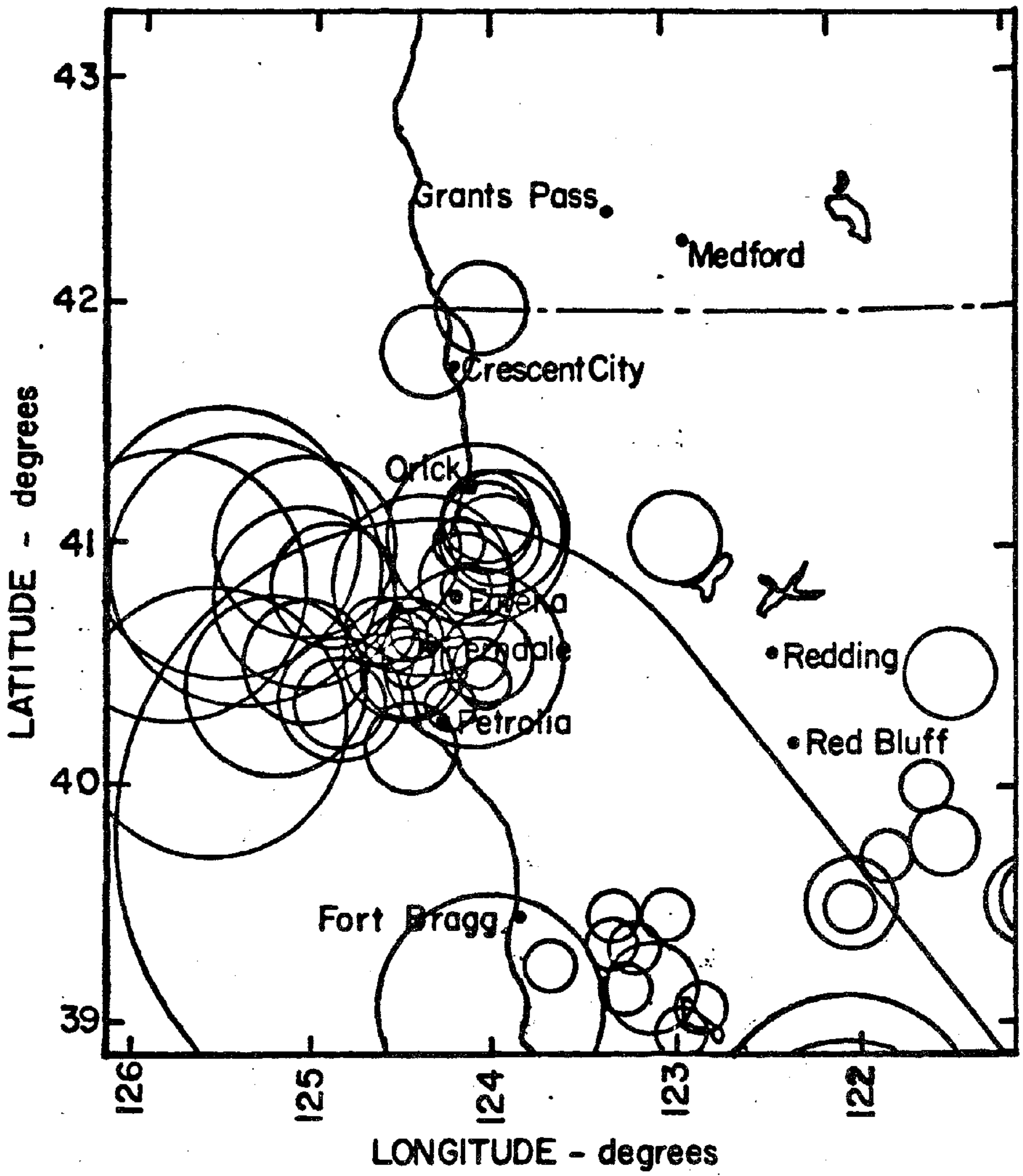

Fig. 9 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES ALONG THE NORTHERN CALIFORNIA COAST, 1870 - 1970.

possible to record a significant number of events during the 100-year period considered.

The projected histories of possible strong-motion recording for Eureka, Ferndale, and Petrolia are shown in Figure 10. The projected histories for Ferndale and Eureka are in close agreement with the actual histories since 1933 when accelerographs were first installed at these sites. This lends credence to the use of these projected histories as a procedure to provide insight into the return of data to be obtained from strong-motion networks in this and similarly active regions. The projected histories indicate return periods of about 3.33 years at Ferndale, about 4 years at Petrolia, and about 8 years at Eureka in recent years. In each case, the rate of return increases significantly after 1906. This could indicate that the Coffman and von Hake compilation is incomplete prior to 1906. Alternatively, it could indicate that the Cape Mendocino region became "stressed" by the slippage to the south of this region in 1906. In the latter case, a fall off of activity should occur as the region adjusts to the stress state imposed by the sudden slippage in 1906. Although this could explain the apparent decrease in rate of return at Eureka, such a decrease in the rate of occurrence does not appear to have occurred at Ferndale or Petrolia. The time interval since 1906 may be too short for such a fall off in activity to be evident in the data from those sites, however.

The instrument stations presently in this region, most of which have been installed under the CSMIP, are shown in Figure 11. This network was established to provide at least one record from any magnitude 6 or greater event and extends well beyond the area of greatest activity. The area near Cape Mendocino has one of the highest rates of activity in the country and is a logical place in which to develop special arrays. The CSMIP has a

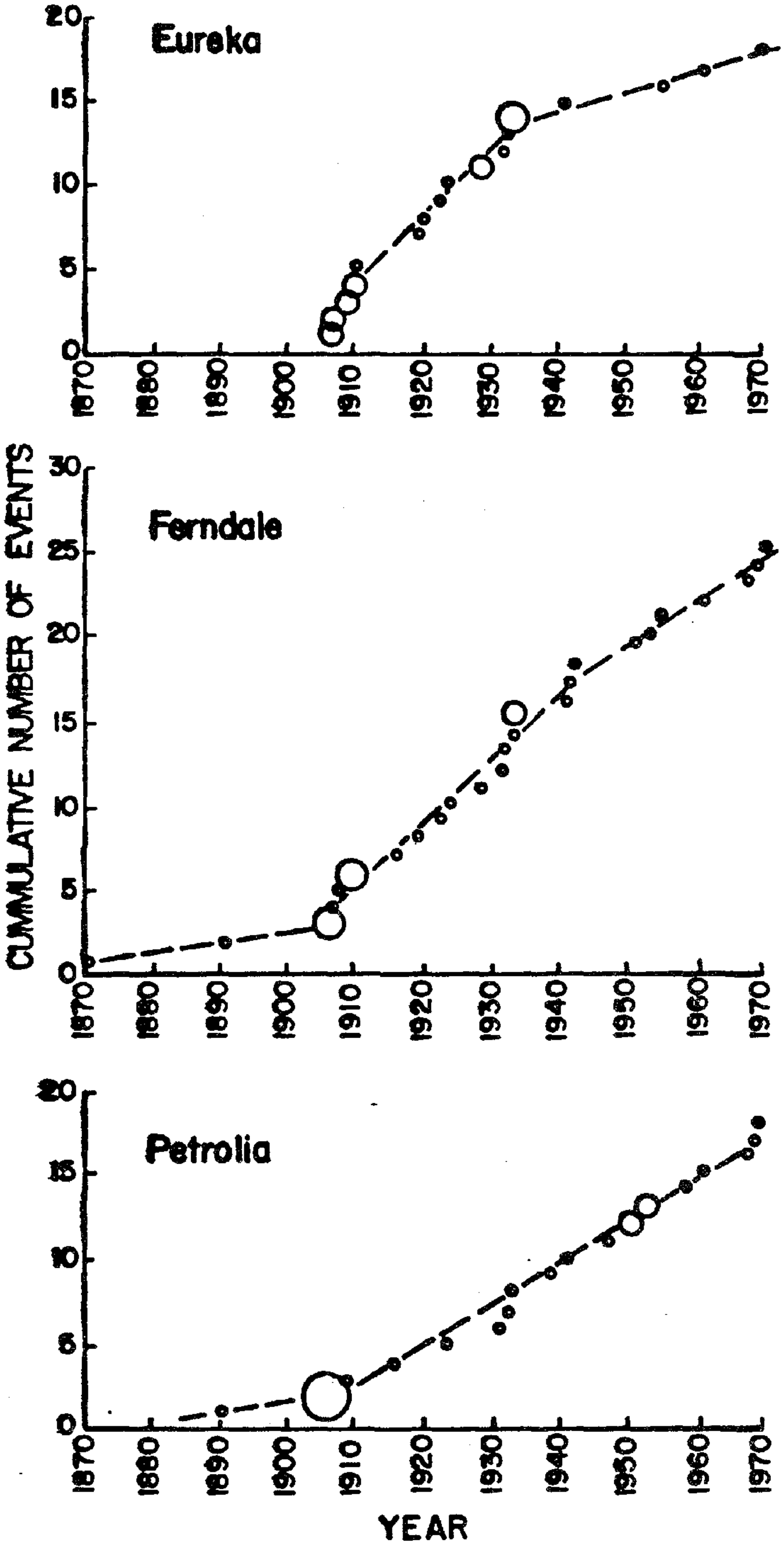

Fig. 10 PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS ALONG THE NORTHERN CALIFORNIA COAST.

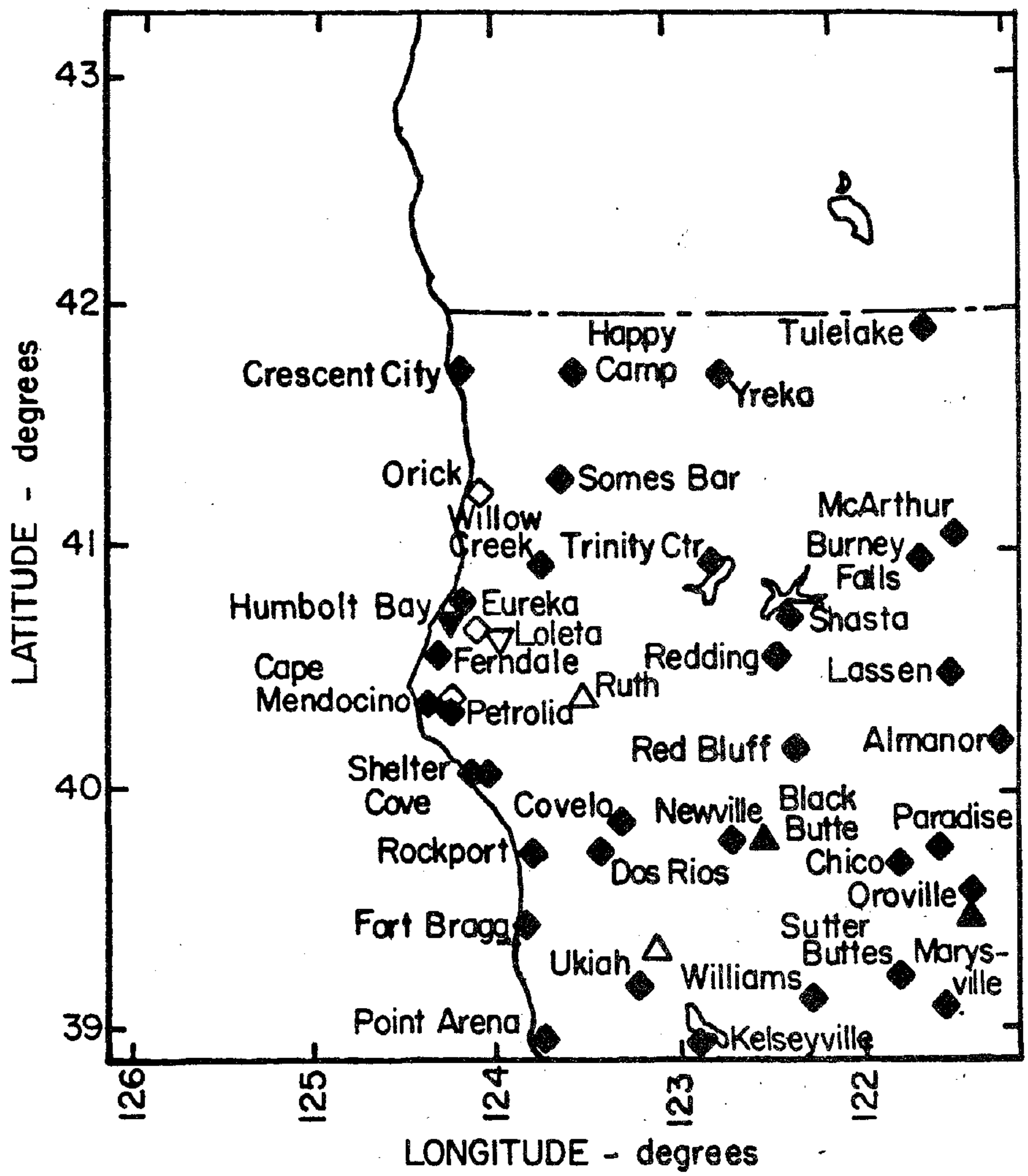

Fig. 11 - STRONG MOTION ACCELEROGRAPH STATIONS IN THE NORTHERN CALIFORNIA COAST REGION. ◆ GROUND STATION, ▲ DAM, ▼ OTHER STRUCTURES. SOLID SYMBOLS INDICATE EXISTING STATIONS. OPEN SYMBOLS INDICATE PROPOSED STATIONS.

"downhole" installation near Petrolia, but additional instrumentation for ground-motion and soil failure studies appears to be warranted. For example, grid-type surface arrays should be installed at the location of the downhole installation and in the Eel River Valley to provide data for studies of site effects. Few candidate buildings exist in the most active area, but the CSMIP will instrument some bridges and a tunnel in this region. Other critical structures close to the active area, such as Ruth Dam on the Mad River, should have at least a minimum level of instrumentation to monitor their response. The nuclear power plant at Humbolt Bay should be thoroughly instrumented as a research study of this type of soil-structural-mechanical system. Although it is not a recently designed plant, valuable data for improving the modelling of such systems would be ensured because of the high level of activity.

The high level of activity offshore suggests that research type studies of ground motions on the ocean bottom should be planned for this area. A variety of ocean bottom conditions ranging from softer deposits off the mouth of the Eel River at Humbolt Bay to firm conditions south of Cape Mendocino are anticipated. Further study is required to identify suitable sites, however.

Central California Coast

The distribution of activity along the central California coast is shown in Figure 12. There is little indication of activity along the San Andreas fault north of Bear Valley. The main zone of activity extends along the Calaveras fault through Hollister and east of Gilroy, along the Hayward fault on the east side of San Francisco Bay, and along the Healdsburg and Rogers Creek faults through Santa Rosa and Ukiah. The greatest concentration of

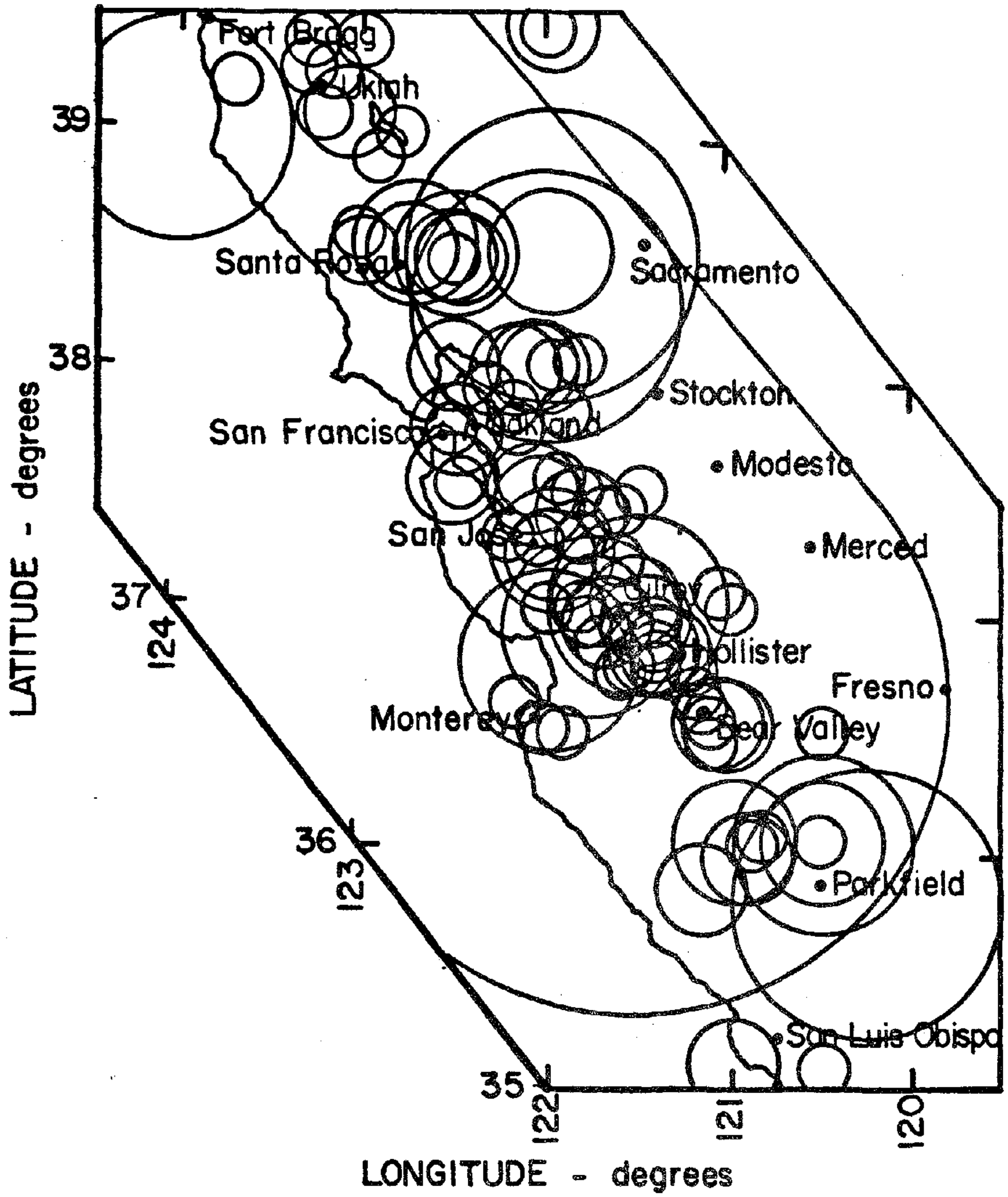

Fig. 12 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES ALONG THE CENTRAL CALIFORNIA COAST, 1870 - 1970.

activity is in the Gilroy to Hollister area.

Projected histories of possible strong-motion recording for several sites in this region are shown in Figures 13 and 14. The activity at Santa Rosa consists of a concentration of events prior to the 1906 earthquake followed by a period of over sixty years in which no strong-motion records could have been obtained. A similar situation exists at San Francisco, where there is a period of over 50 years after the 1906 event before another record could have been obtained. This projected history is confirmed by the actual history of recording at Golden Gate Park and in downtown San Francisco. Between 1933, when instruments were first installed, and the 1957 Daly City event no records were obtained at Golden Gate Park, and the records obtained at other stations in San Francisco were of small amplitude. At Oakland and San Jose, both of which are relatively close to the Hayward fault, there appears to be a more regular occurrence of strong-motion events with an average return period of about 12 years for the entire period considered. This is higher than the return period obtained from the actual recordings at Oakland since 1933. The projected history at Hollister is in agreement with the actual history of strong-motion recording at that site since 1940, but it indicates a quiescent period from 1906 to 1940. Hollister is near the southern end of the 1906 fault rupture. This suggests that the state of stress in the Hollister area was relieved by the 1906 event and that the present return period of 4 years per event is a return to "normal". Bear Valley and Parkfield both exhibit a regular recurrence of strong ground motion, with higher levels of motion occurring at Parkfield.

The number of strong-motion accelerographs currently installed in this region is shown in Figure 15. Although this appears to be adequate for general studies, a careful review should be made to determine if the

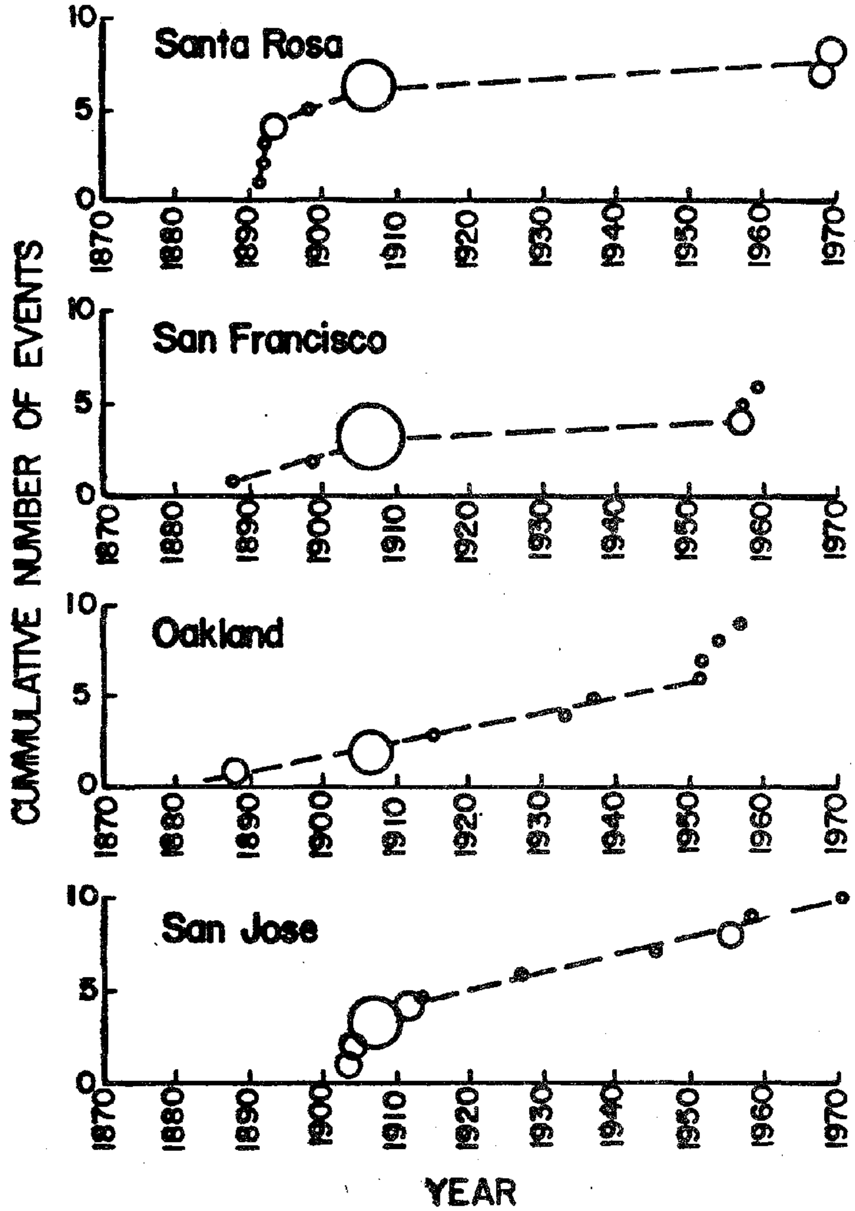

Fig. 13 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS ALONG THE CENTRAL CALIFORNIA COAST.

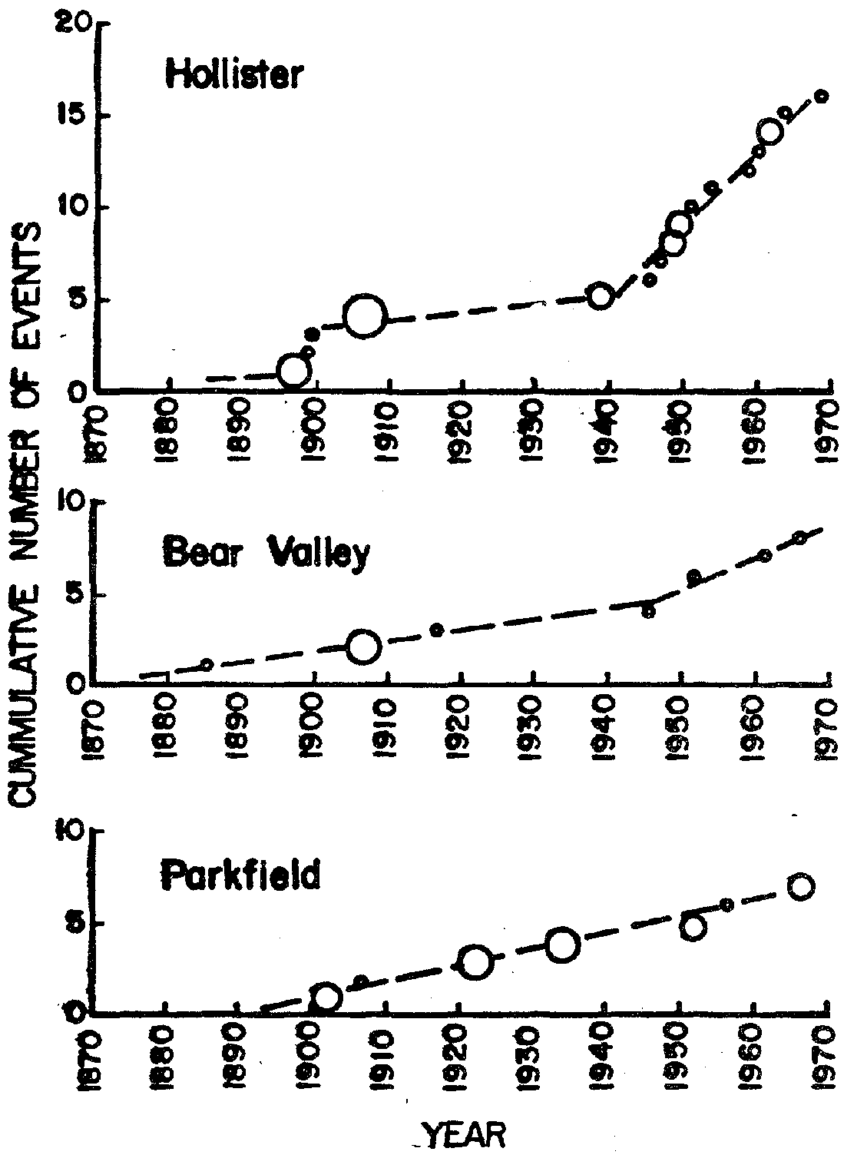

Fig. 14 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS ALONG THE CENTRAL CALIFORNIA COAST.

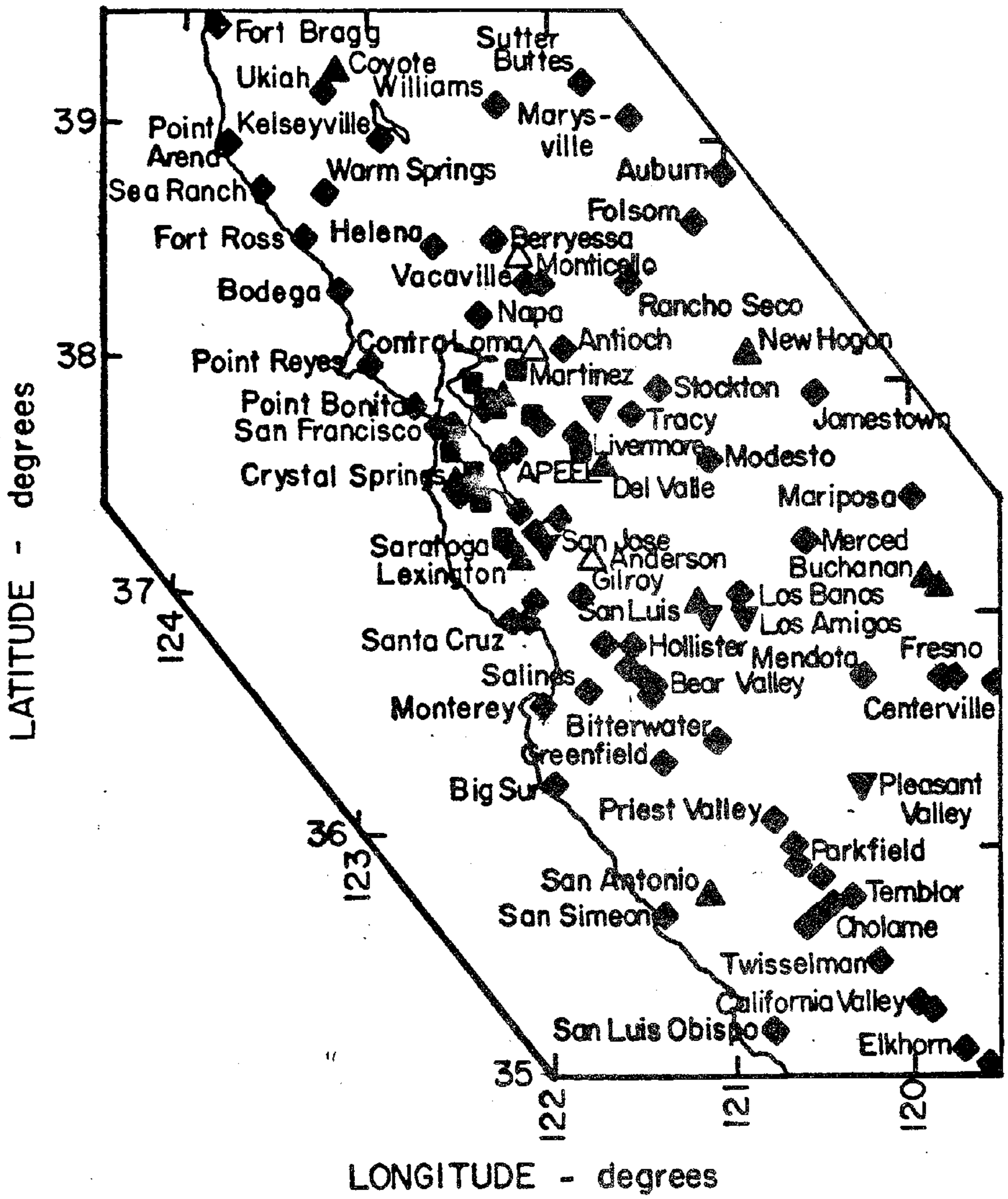

Fig. 15 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE CENTRAL CALIFORNIA COASTAL REGION. ◆ GROUND STATIONS, ▲ DAMS, ■ BUILDINGS, ▼ OTHER STRUCTURES.

instruments in their present locations will provide adequate data to answer all of the unanswered questions regarding ground motion and structural response during a magnitude 8 earthquake on the San Andreas fault. For example, a plan had been outlined to extend the APEEL Array (Morrill, 1972) from the Pacific Ocean to the Livermore Valley. Similarly, a plan had been outlined for an array extending from Point Reyes to the Central Valley (CDMG, 1976). These arrays would have crossed the San Andreas, Hayward, and Calaveras Faults (or their northern extentions). The plans included consideration of source mechanism studies, all aspects of ground motion, and would have tied into structural response studies. More instrumentation for special studies should be located in the zone of highest activity. Selected buildings along the Hayward fault should be instrumented, and all nearby critical facilities such as dams should be instrumented so as to monitor their response. Special instrumentation, such as that installed at Richmond by the University of California to study the influence of the soft bay muds or that installed by the CSMIP at San Benito to study site effects should be installed in the active areas. A grid-type array to study site effects should be planned for the Gilroy to Hollister area, and the dam at Anderson Reservoir should be extensively instrumented as a research project because of the high rate of activity in the area.

Southern California

The distribution of strong-motion activity in southern California is indicated in Figure 16. The activity is concentrated in the Imperial Valley, along the Transverse Ranges, and in the vicinity of the epicenter of the 1952 Kern County earthquake. The trace of the San Andreas fault is not evident in the locations of the events plotted. This is reasonable in view of the

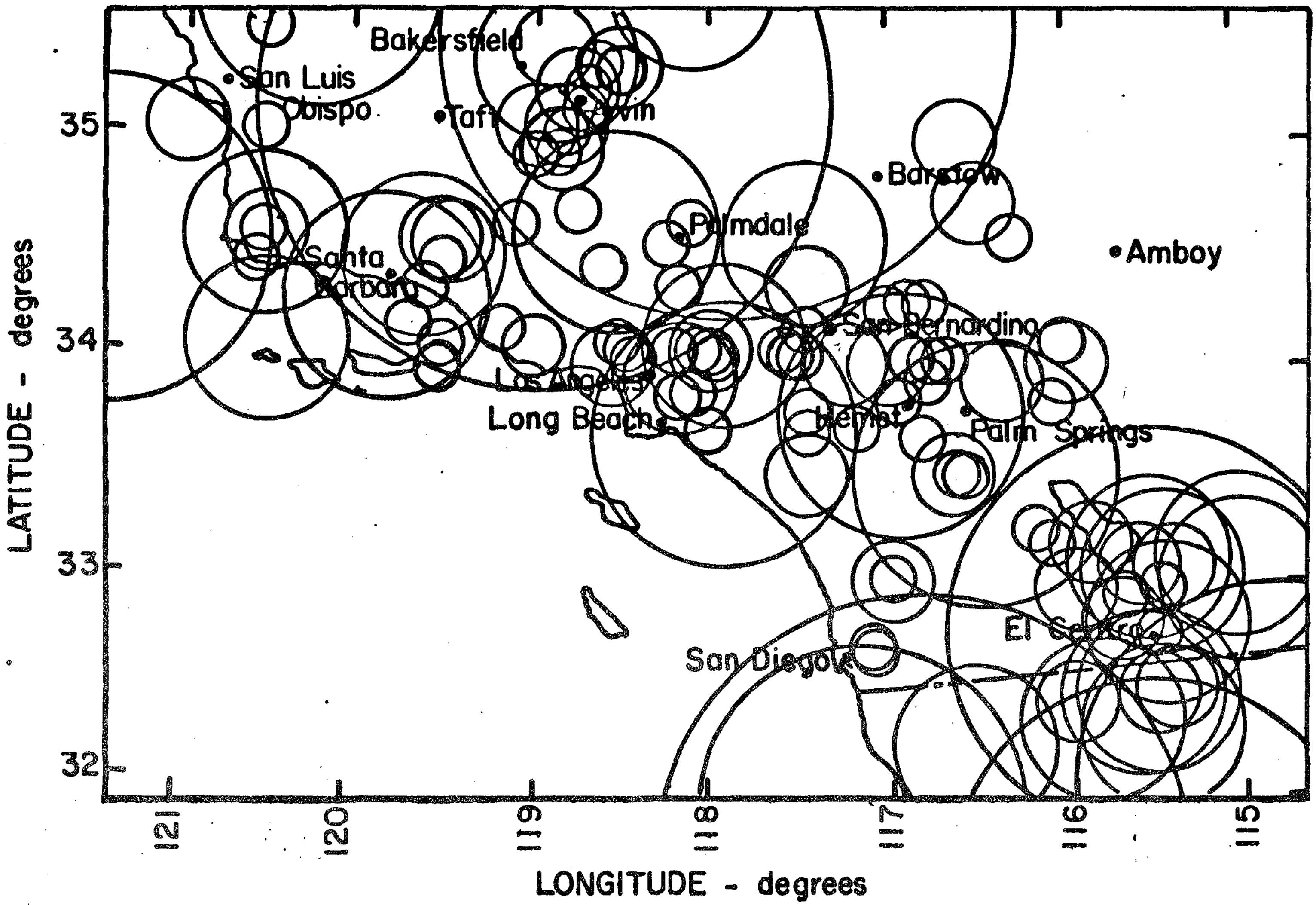

Fig. 16 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN SOUTHERN CALIFORNIA, 1870 - 1970.

occurrence of a major earthquake at Fort Tejon in 1857 and the observation that the activity along the San Andreas fault from Cholame to San Bernardino is dominated by major events occurring at infrequent intervals (100- to 500-year return periods).

The projected histories of recording at selected sites in southern California are shown in Figures 17 and 18. All of these projections suggest that the seismic history prior to 1900 is incomplete. On the other hand, this may reflect a period of inactivity following the major earthquake at Fort Tejon in 1857. Several of the projected histories indicate significant concentrations of activity in relatively short time intervals but with average return periods of approximately 11 years. This generally high level of activity in the transverse ranges suggests that this is a region in which further development of the existing instrument networks should take place.

The locations of the instruments in the region are indicated in Figure 19. These locations were selected by a variety of organizations with different objectives. Although most of the significant strong-motion records obtained in the U.S. to date have come from instruments located in this region, a detailed review should be made to determine the specific types of problems that can be solved when data is obtained from the instruments in their present locations. A more carefully planned network may provide for a better interpretation of the results from a future event. For example, a grid-type array has been proposed for the Los Angeles basin (Trifunac and Teng, 1977). The objective of that proposal was to permit modelling of the near-surface geology. This would lead to a more complete interpretation of the nature of the ground motion throughout the basin, and this would allow more complete interpretations to be made of the damage patterns in future earthquakes than is possible at present. The existence of a wide variety of

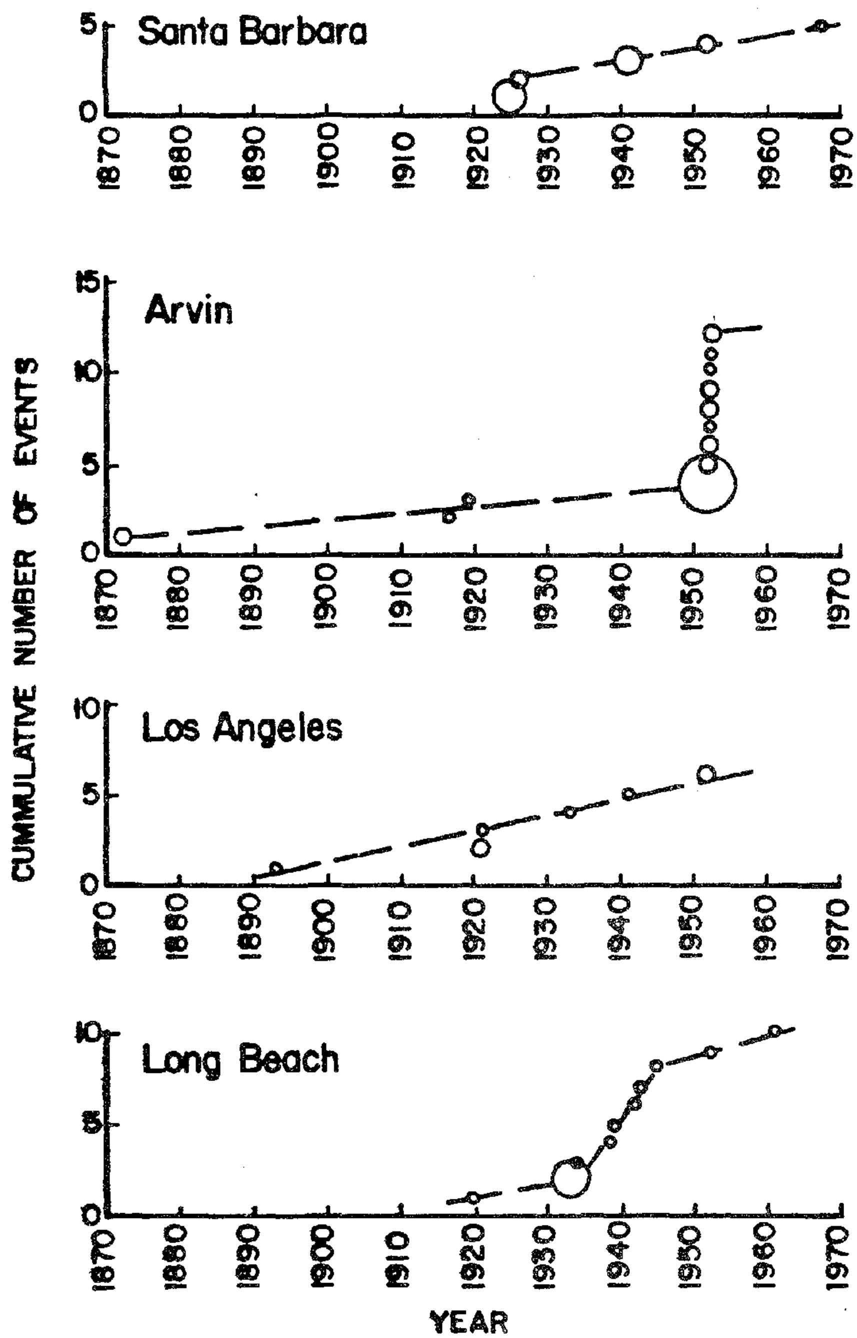

Fig. 17 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN SOUTHERN CALIFORNIA.

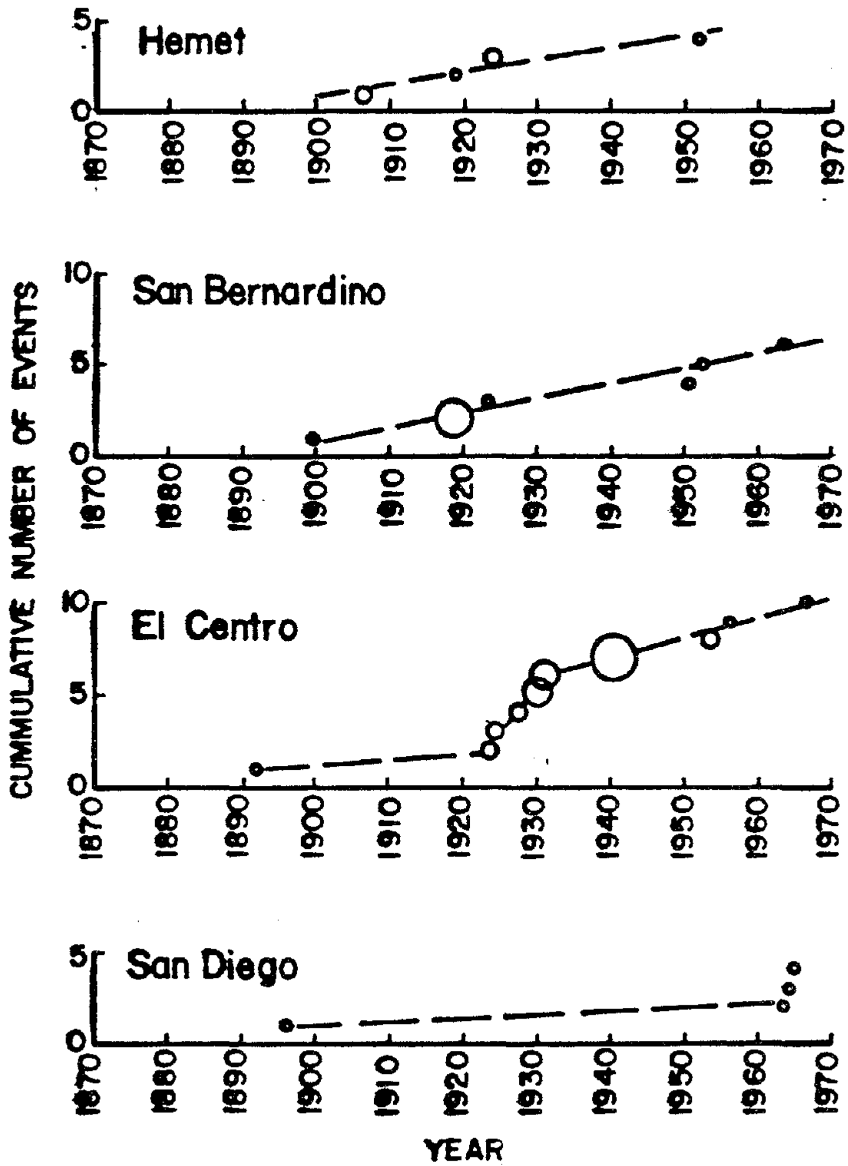

Fig. 18 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN SOUTHERN CALIFORNIA.

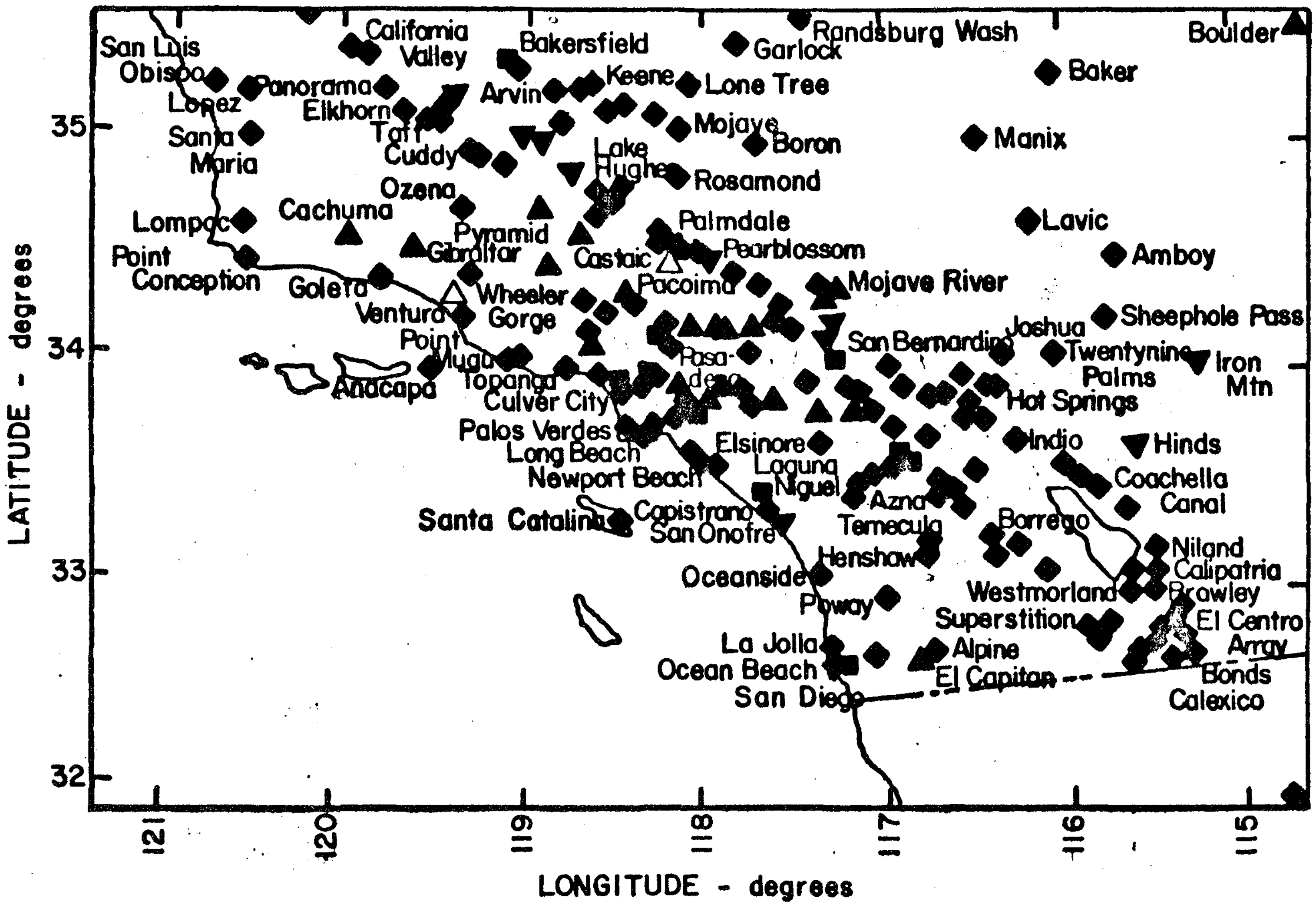

Fig. 19 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE SOUTHERN CALIFORNIA REGION. ◆ GROUND STATIONS, ▲ DAMS, ■ BUILDINGS, ▼ OTHER STRUCTURES.

structures in this relatively active region also provides a unique opportunity to develop a well-planned program of structural response studies in conjunction with the ground motion studies. For this purpose, some of the instrumentation that is required by the local building codes might be upgraded. Some of the dams located in the Transverse Ranges have a minimum level of instrumentation at present, and consideration should be given to more extensive instrumentation for research purposes. Finally, the locations of the instruments should be reviewed relative to the minimum amount of data that is desired when another magnitude 8 earthquake occurs on the San Andreas fault. The CSMIP and Caltech have installed several special arrays for this purpose.

Eastern California and Nevada

The distribution of activity in eastern California and western Nevada is indicated in Figure 20. The activity occurs along the eastern front of the Sierra Nevada (Walker Pass to Susanville) and along a generally north-south line from Bishop to Lovelock. The activity along the eastern front of the Sierra Nevada consists of numerous small events distributed in such a way that at most sites no more than three records would have been obtained during the 100-year period considered. The activity along the north-south line from Bishop to Lovelock consists of a sequence of major events but few small events. In this region of major events, there are sites at which four or five events could have been recorded, but there are also large areas in which only one, or at most two events would have been recorded in the 100-year period considered.

The activity in this region and its relationship to active faults, to a postulated long range "seismic cycle", and to the current microearthquake activity has been discussed in detail by Ryall (1977). Ryall's conclusions

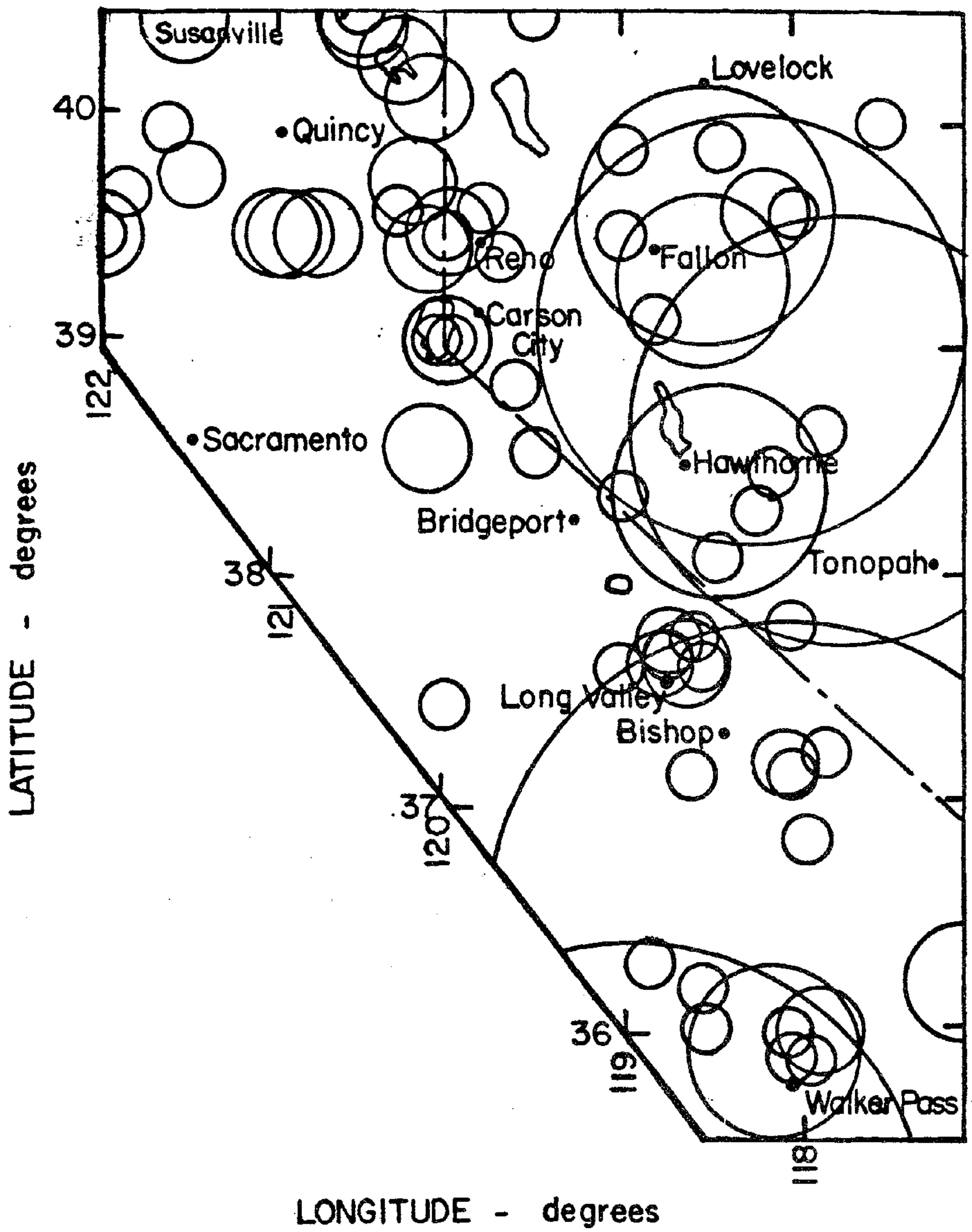

Fig. 20 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN EASTERN CALIFORNIA AND NEVADA, 1870 - 1970.

are worth repeating because of their direct relevance to the current study:

"1. The seismic 'cycle' in Nevada is of the order of thousands of years long. A typical large (M = 7) earthquake is followed by aftershocks lasting about a century, and activity in the rupture zone then stabilizes for a long period of time. Foreshock activity appears to consist of a moderate increase in seismicity in the zone of an impending rupture and occurs for at least several decades before the main shock.

2. The epicentral distribution of large earthquakes that have occurred during the historic period is inadequate for the determination of seismic potential. In fact, based on the evidence presented ..., rupture zones of recent large Nevada earthquakes may be seismically 'safe' for hundreds or even thousands of years.

3. Maps of late Quaternary faulting are also inadequate for detailed seismic zoning. Faults considered 'active' on strictly geological criteria are rather evenly distributed over most of the Nevada region, and great earthquakes have occurred in areas where geologic evidence of active faulting is either missing or obscured by erosion.

4. Analysis of small earthquakes for 1970-1974 indicates that most of the region has a background level of minor seismicity. One area of numerous earthquakes and relatively high seismic energy release is the region between the rupture zones of the great 1872 Owens Valley and 1932 Cedar Mountains earthquakes. Epicentral scatter and complex structure suggests that this zone may be one in which tectonic stress is relieved continuously by small-to-moderate earthquakes, but the possibility of a great earthquake there is not ruled out by the data analyzed.

5. In western Nevada and eastern California, in the region bounded by a line from Pyramid Lake to Walker Lake to Bridgeport to Quincy, small earthquakes for the 1970-1975 period line up along a number of northwest zones that are up to 110 km long. Some of these zones correlate well spatially with mapped geologic faults in the region, and some extend mapped faults into areas (e.g., Pyramid Lake, Lake Lahonton areas) where faults may be obscured by weathering or bodies of water. The continuity of the epicenter lineups and their agreement with mapped faults suggest that this region has high potential for large earthquakes in the future."

The projected histories of possible strong-motion recording for several sites in this region are shown in Figure 21. Walker Pass, at the southern end of the zone of the 1872 Owens Valley earthquake, experienced a long period of inactivity following that event. The increase in activity in 1946 could represent a return to "normal" activity or the beginning of a buildup

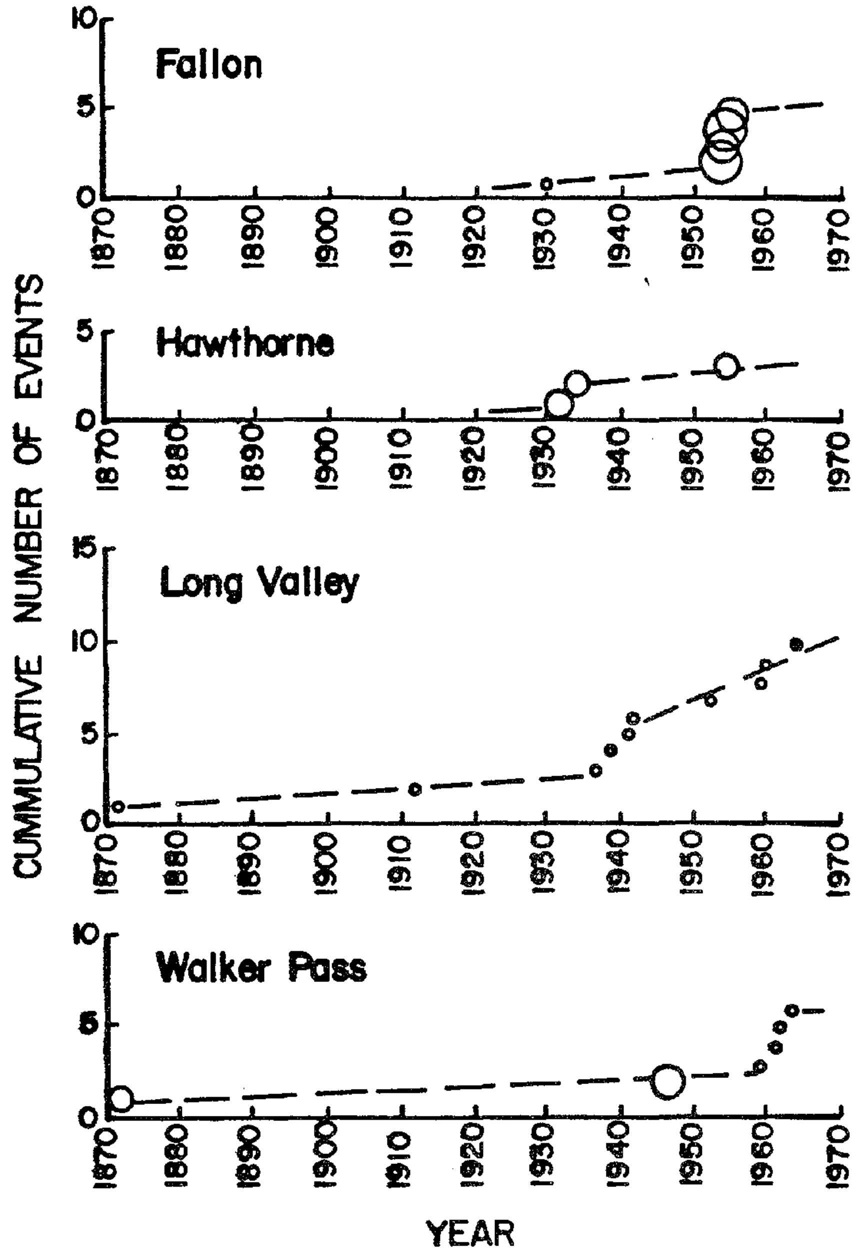

Fig. 21 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN EASTERN CALIFORNIA AND NEVADA.

to a major event. In the latter case, as Ryall suggests, several decades may elapse before a major event occurs. The projected history of recording at Long Valley, at the northern end of the zone of the 1872 Owens Valley event, indicates a significant increase in activity beginning in 1936. Long Valley is in the zone of activity indicated in Ryall's fourth conclusion, and the increase in activity in this area follows the occurrence of the 1933-1934 Excelsior Mountain earthquakes. The history from strong-motion records obtained at Bishop since 1934 indicates a higher activity than the projected history, but it correlates well with the projected history at Long Valley. The projected history of possible recording at Fallon probably is characteristic of the "typical" site in the north-south trend of major events in Nevada. There is a long period of inactivity followed by a series of events prior to or following a major event and then a period of inactivity when no records would be obtained.

The CSMIP has provided a reasonably dense network of instruments in the eastern part of California, as indicated in Figure 22, but that network is incomplete without an appropriate amount of instrumentation in the adjacent regions of Nevada. Additional instruments for measuring ground motion in the areas where major events have occurred or where there appears to be a buildup of activity would complement the instrumentation that the CSMIP has placed in eastern California. As Ryall has indicated, the next major event may not occur in the region for another 500 to 1000 years, but the minimum level of instrumentation indicated is suggested so as to obtain at least one record from any magnitude 6 or greater event that occurs in this region. Because of the relatively low level of activity at individual sites in this region, only a minimum level of instrumentation should be installed on critical structures such as dams.

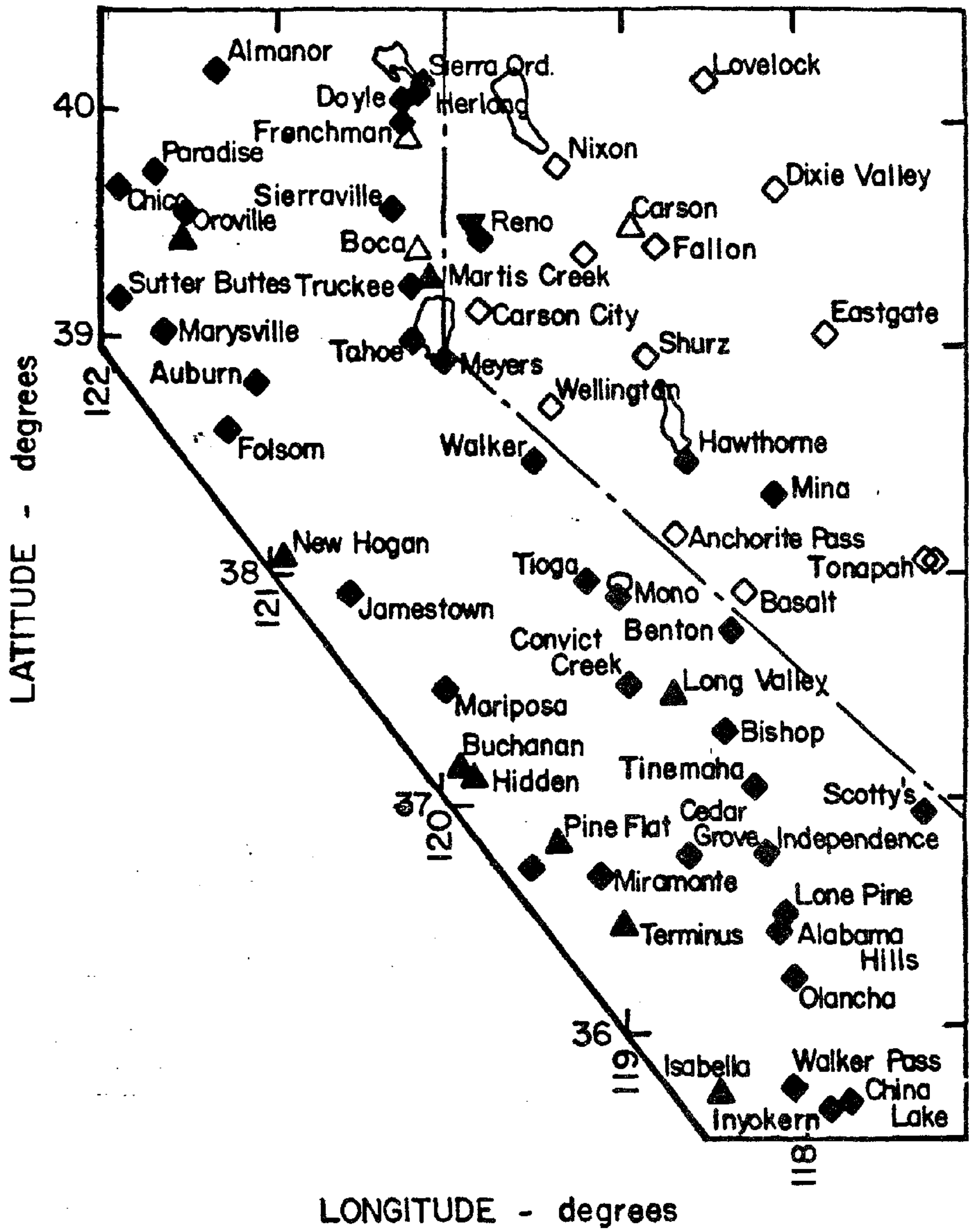

Fig. 22 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE EASTERN CALIFORNIA AND NEVADA REGION. ◆ GROUND STATIONS, ▲ DAMS, ■ BUILDINGS, ▲ OTHER STRUCTURES.

Implicit in Ryall's conclusions and in the trends indicated by the present study is the observation that the successful development of a strong-motion instrument network in this region may depend on a continuous monitoring of the trends indicated by microearthquake activity. In any particular 100-year period, strong-motion records may be obtained from a few significant events (different ones at different sites), but at some time, which cannot be determined by the current seismic activity, a major event affecting many such sites will occur. Ryall also implies that the zone of activity could shift farther to the east in the future.

Pacific Northwest

As may be seen from Figure 2, the areas of highest strong-motion activity in the Pacific Northwest are in the Puget Sound trough and near Portland, Oregon. The details of the distribution of activity in this region are shown in Figure 23 (see: Rasmusen and others, 1973, also). In the northern portion of the Puget Sound trough the only sites at which more than one strong-motion record could have been obtained are between Bellingham and the Canadian border. In the area between Seattle and Olympia three records might have been obtained at most sites.

The projected histories of possible strong-motion recording from 1870 to 1970 for selected sites in the Pacific Northwest are shown in Figure 24. These projected histories indicate a relatively quiescent period prior to 1940. Since 1940, a significant rate of return is evident only at Tacoma, which is located between the epicenters of the two significant events that have occurred in the Northwest in the period considered. The projected history for Olympia indicates that no record would have been obtained in 1965, whereas strong-motion records were obtained at Olympia in 1949 and 1965.

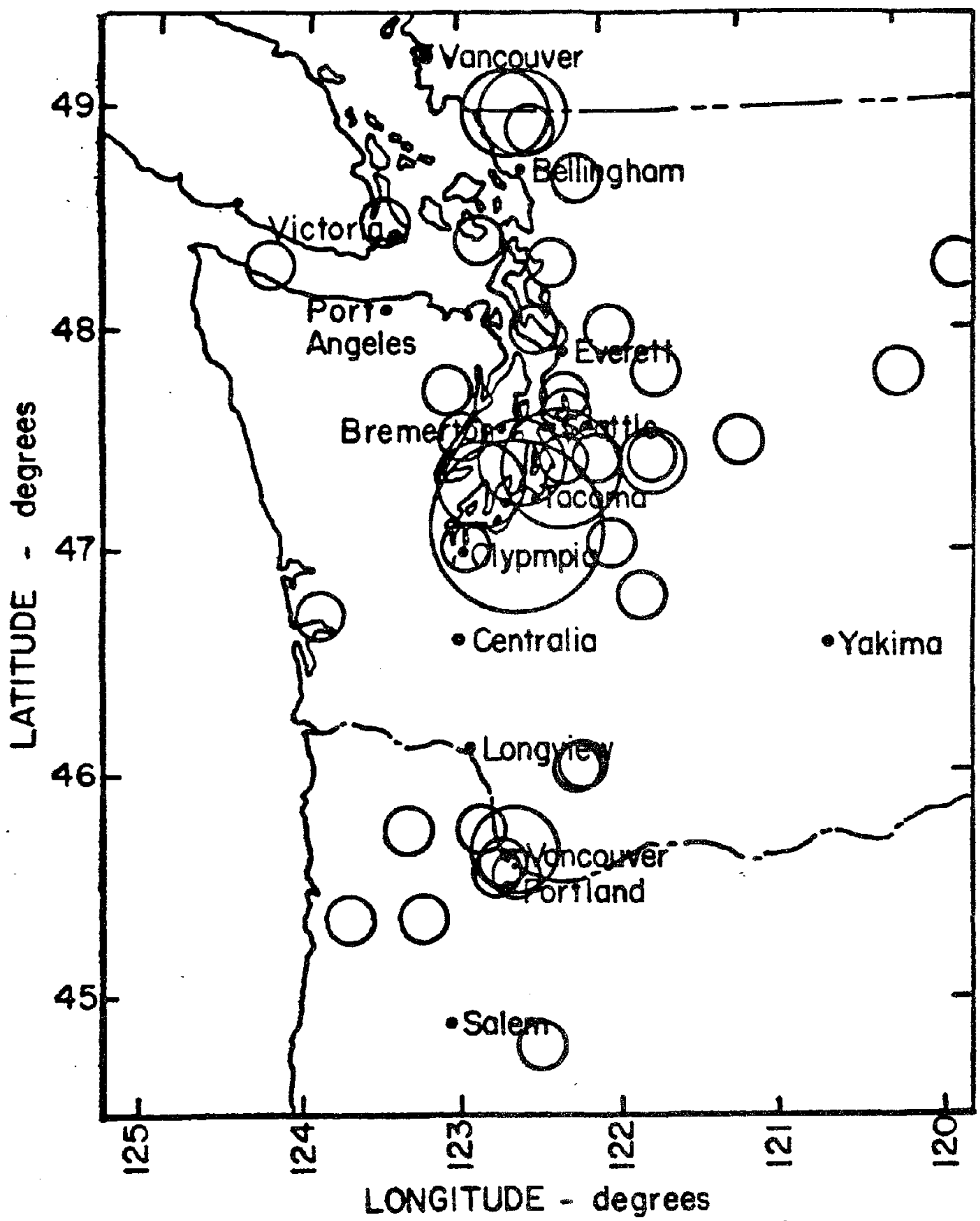

Fig. 23. MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN THE PACIFIC NORTHWEST, 1870 - 1970.

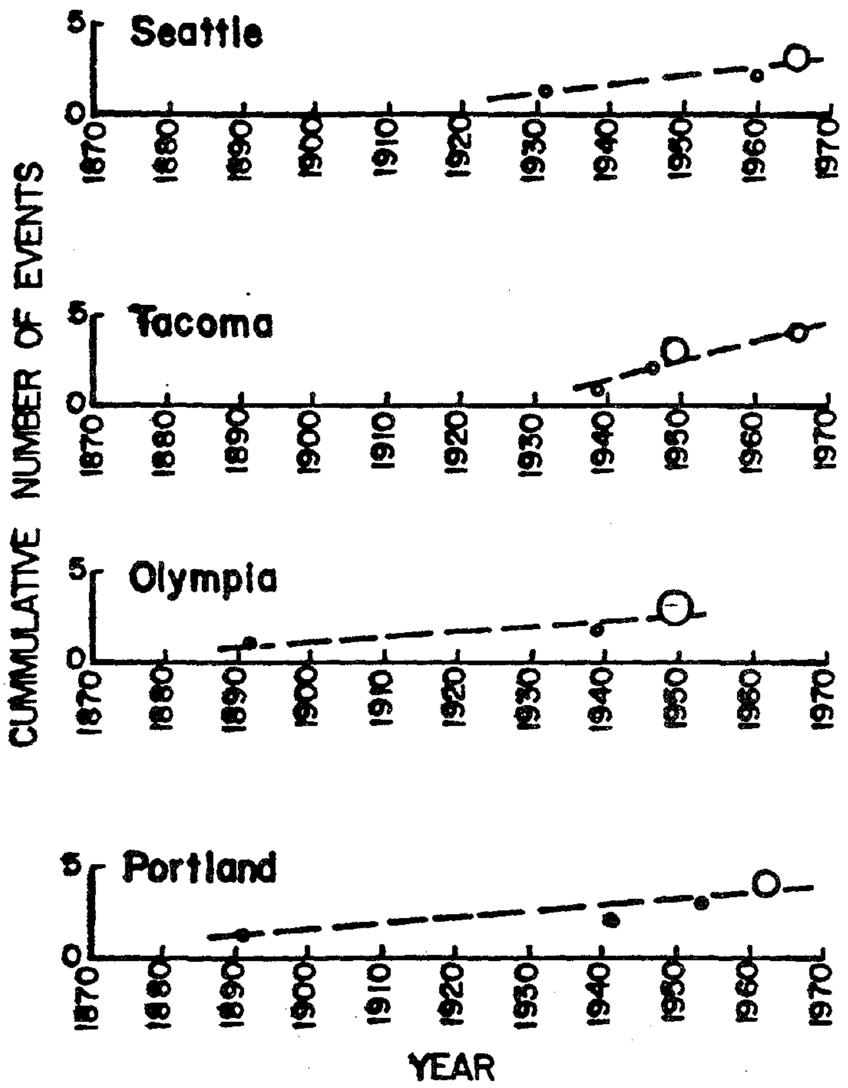

Fig. 24 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN THE PACIFIC NORTHWEST.

The indication of relatively little activity in the Northwest prior to 1940 may reflect an incomplete historical record. On the other hand, this raises serious questions regarding any extrapolation into the near future. If the rate of activity did increase in 1940, how long will it continue at that rate? Is the dispersed, low-level activity in the northern part of the Puget Sound trough an indication of a buildup to a major event? What is the relation between the activity in the Puget Sound trough and that in British Columbia, where several major events have occurred? Where is the next major event in the entire region most likely to occur? There is no clear evidence in the historical record to answer these questions.

The level of activity in this region does not warrant the development of special arrays or detailed studies, but a minimum level of instrumentation should be installed to determine the general characteristics of ground motion and to monitor the response of critical structures in the region. At the present time, the instruments in the region are concentrated in the Seattle area, which does not appear to be the best use of these instruments. A network of instruments throughout the Puget Sound trough but with some concentration in the southern portion is suggested. Such an instrumentation plan is indicated in Figure 25. This would involve a redistribution of instruments already in the region and should include the replacement of the older accelerographs maintained by the University of Washington.

The City of Tacoma has adopted an ordinance that provides funding for maintenance of instruments in 6 to 10 structures. The efforts to develop that program should be supported. Critical structures such as dams should be instrumented, also. The Corps of Engineers and the Bureau of Reclamation are monitoring the response of the dams under their jurisdictions, and the Seattle Light and Power Co. is planning to expand the instrumentation at Ross Dam

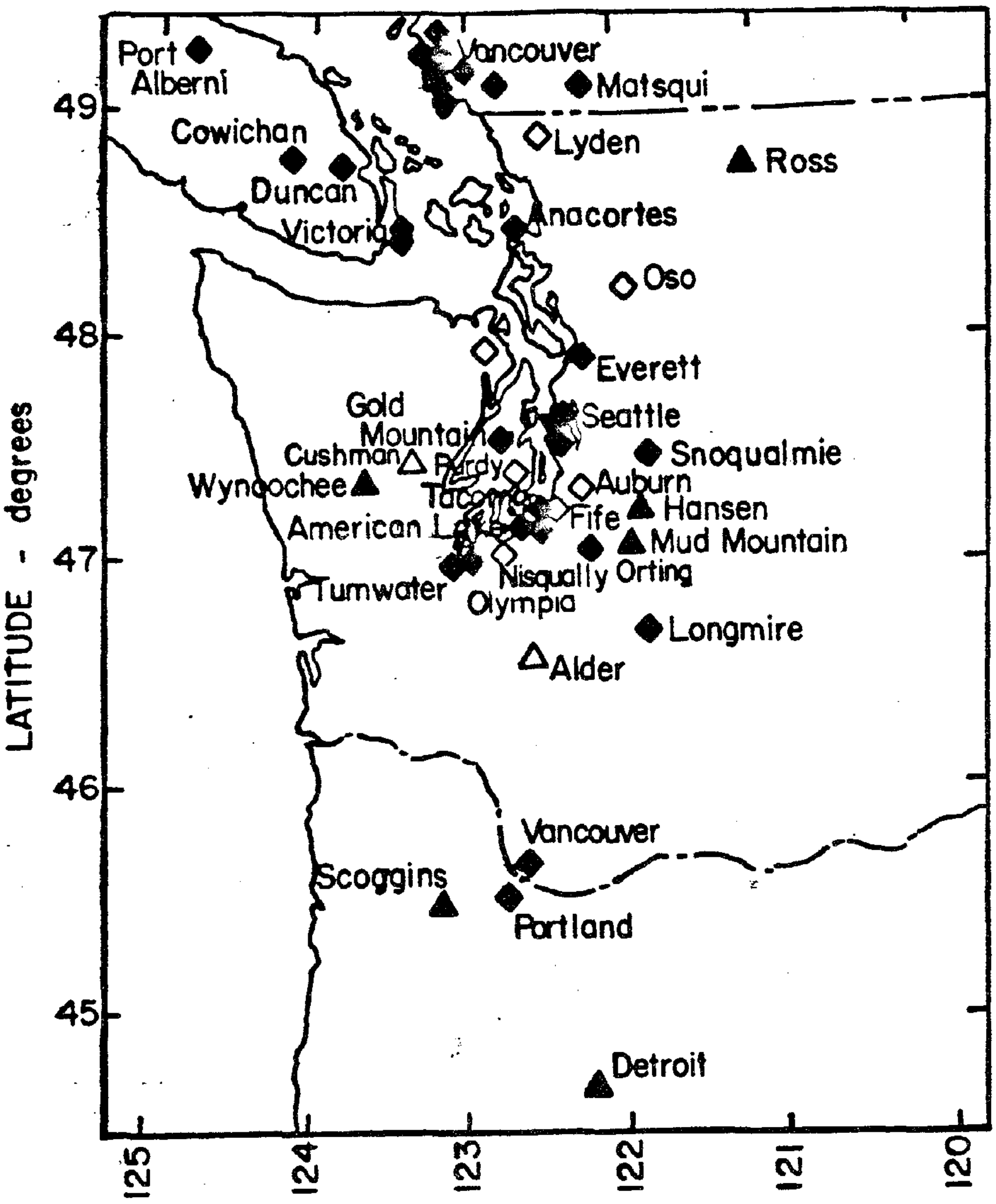

Fig. 25 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE PACIFIC NORTWEST. ◆ GROUND STATIONS, ▲ DAMS, ■ BUILDINGS. ▼ OTHER STRUCTURES.

when the height of the dam is increased.

The trends indicated by microearthquake activity in the region could be important to the development an appropriate strong-motion network, so that the existing network of sensitive seismographs in the region should be supported and possibly expanded.

Northern Rockies

The region of the northern Rocky Mountains from Flathead Lake, Montana to Yellowstone Park has been the location of several significant earthquakes and is a region of sporadic activity. Three subregions of historic activity can be identified: Flathead Lake, Helena-Three Forks, and Centennial Valley-Yellowstone Park. The Flathead Lake subregion lies at the southern end of the Rocky Mountain trench, in a zone of normal faulting (Stevenson, 1976). The Helena-Three Forks subregion lies along the Montana overthrust belt that extends from Three Forks north through Glacier Park into Canada. The Centennial Valley-Yellowstone Park subregion is comprised of at least three zones of north or east trending normal faults (Trimble and Smith, 1975).

The distribution of MMI = VI and greater events in this region during the period from 1870 to 1970 is shown in Figure 26. In general, the activity is concentrated around the locations of the significant historic events. Large areas within the region have been "inactive" during the time period considered, but the major faulting and tectonics of the region suggest that many areas within this region could become "active" at any time.

The projected histories of possible strong-motion recording at several sites are shown in Figure 27. At any individual site, the events that could produce significant strong-motion records occur within a short period of time

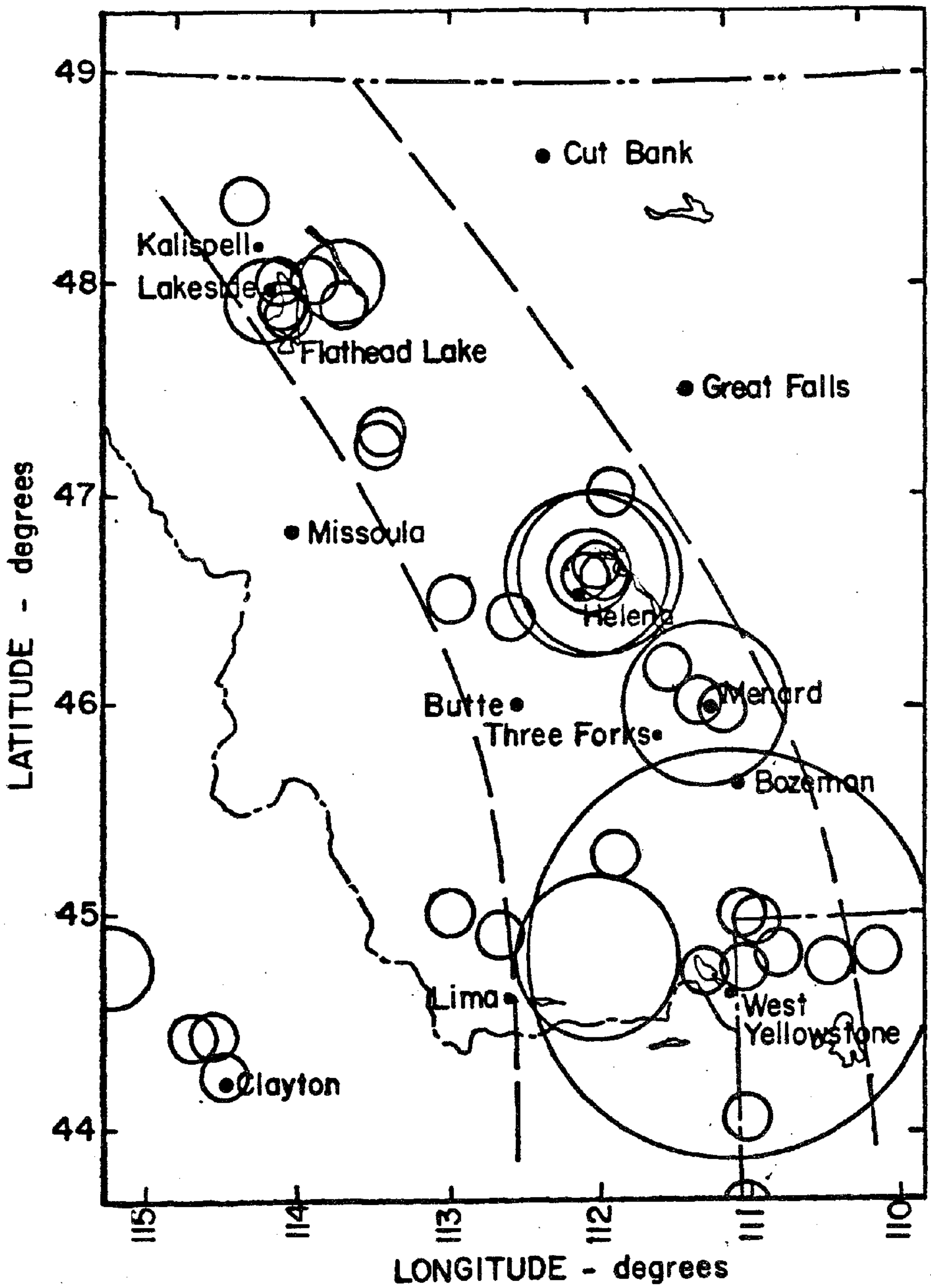

Fig. 26 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN THE NORTHERN ROCKY MOUNTAIN REGION, 1870 - 1970.

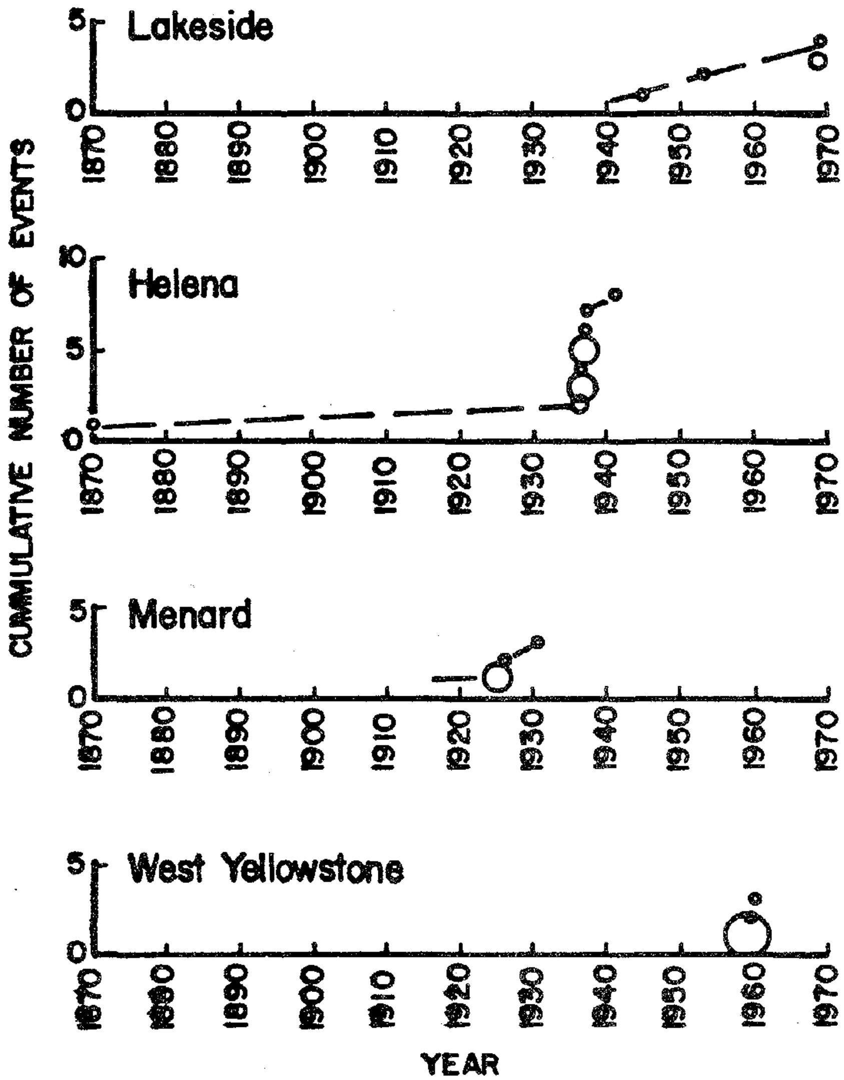

Fig. 27 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN THE NORTHERN ROCKY MOUNTAIN REGION.

before or after a major event. Furthermore, there is no evidence in the seismic history available (the total history that is reported in the compilation by Coffman and von Hake has been utilized) to indicate that the concept of a "return" period or a "recurrence" relationship can be applied to the strong-motion activity at any specific site in this region. The buildup of activity in the area of Flathead Lake since 1945 suggests that this may be the location of a major event in the near future, but there is no evidence that would permit an accurate "prediction" of when it might occur.

A network of instrumentation such as that indicated in Figure 28 should provide at least one and possibly two ground motion records from any major event associated with one of the three subregions. The Veterans Administration, the Bureau of Reclamation, and the Corps of Engineers have instruments at most of their facilities in this area.

A detailed and continuous study of the trends indicated by micro-earthquake activity in the region within the dashed lines in Figure 26 should be conducted to aid in the development of a strong-motion network.

Utah and Southeastern Idaho

In this region, there is an arc of activity that extends along a zone of normal faults from the southwest corner of Utah through the Wasatch front and into southeastern Idaho. It is widely recognized (see, for example, Smith, 1974) that the Wasatch front has been the source of major earthquakes in the past and is likely to be in the future.

As shown in Figure 29, the strong-motion activity in this region is spatially dispersed. At most sites, no more than one significant record would have been obtained. Furthermore, within the zone indicated by the dashed lines in Figure 29 there was less than a fifty percent chance that a

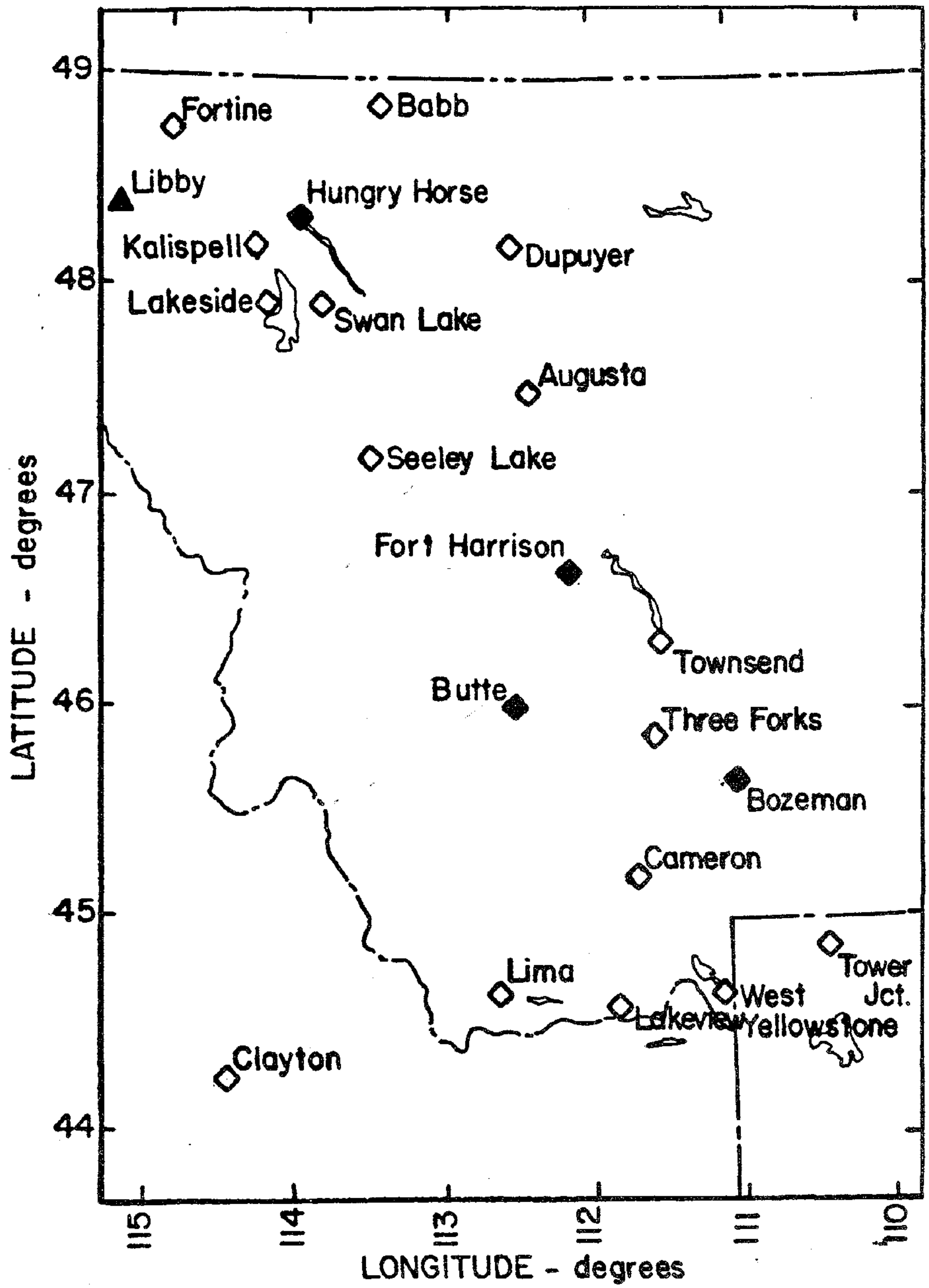

Fig. 28 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE NORTHERN ROCKY MOUNTAIN REGION. ◆ GROUND STATIONS, ▲ DAMS.

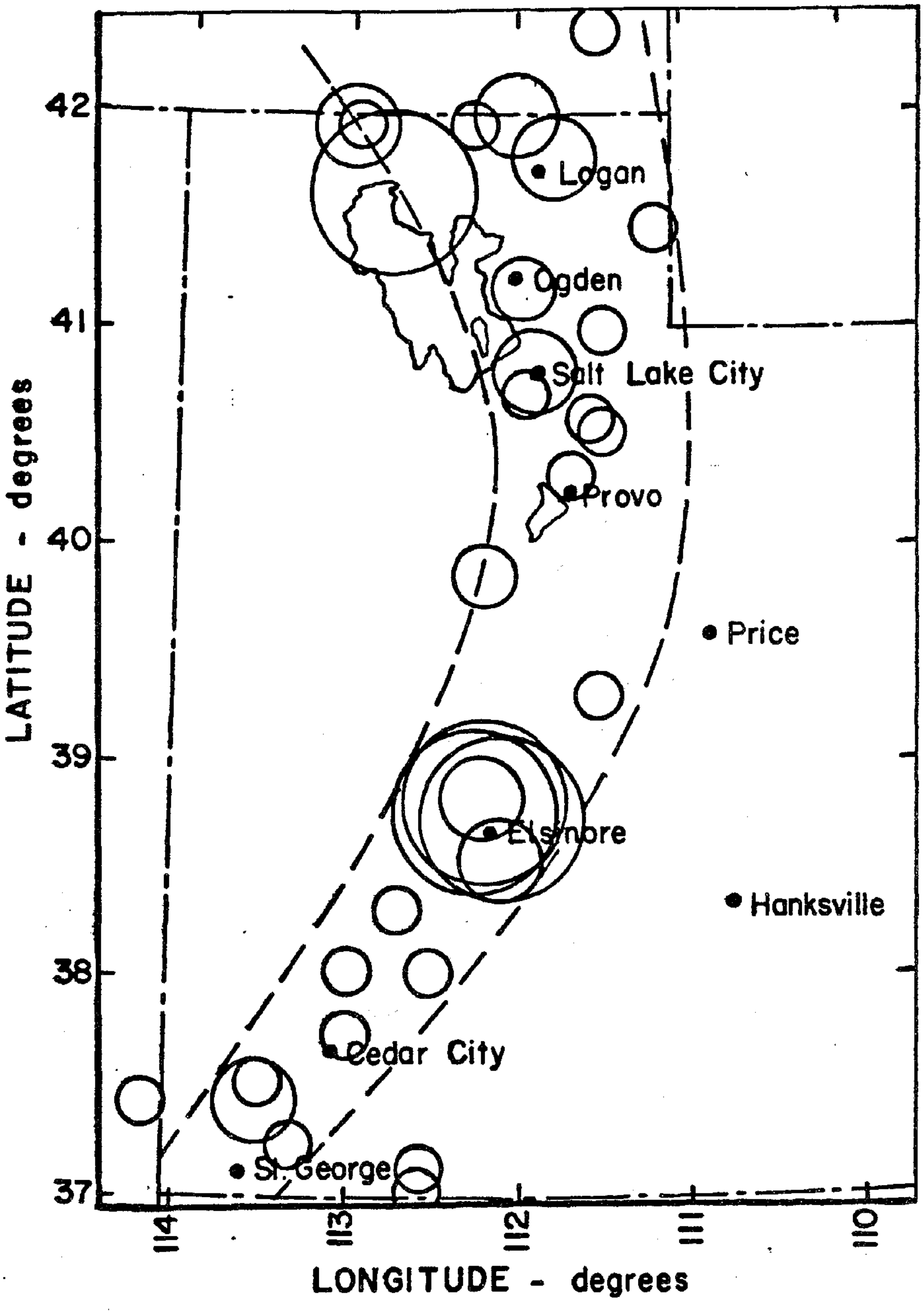

Fig. 29 MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN UTAH AND SOUTHEASTERN IDAHO, 1870 - 1970.

site would have been selected at which even one record above the threshold level could have been obtained during the 100-year period considered (that is, there is a greater area in which no records could have been obtained than there is area in which at least one record could have been obtained).

Projected histories of possible strong-motion recording at sites in this region are shown in Figure 30. The projected history of strong-motion recording at Elsinor consists of one event in 1900, one in 1910, a series of three in 1920 - 1921, and one in 1968. At other sites in this region, generally only one or two strong-motion records could have been obtained in the 100-year period from 1870 to 1970 (the entire seismic history compiled by Coffman and von Hake for this region).

The temporal and spatial dispersion of the activity in this region can be interpreted as an indication that the release of strain buildup is gradual over the entire region and that no events larger than the MMI = VIII events that have occurred in the historic record are likely to occur in the future. Alternatively, one can assume that the dispersed nature of the activity is an indication that a buildup to a sequence of large events is occurring. Such a sequence could be similar to that which occurred in eastern California and Nevada over a period of more than a century (1845 - 1954) with intervals of 20 to 25 years between MMI = X or greater events. The size of the fault scarps along the Wasatch front, which implies that major earthquakes have occurred and are likely to occur again, suggests that the latter interpretation is the more plausible.

For planning purposes, the dispersed nature of the activity will be assumed to continue into the near future (that is, within the normal lifetime of a strong-motion instrument), so that only a minimum strong-motion network

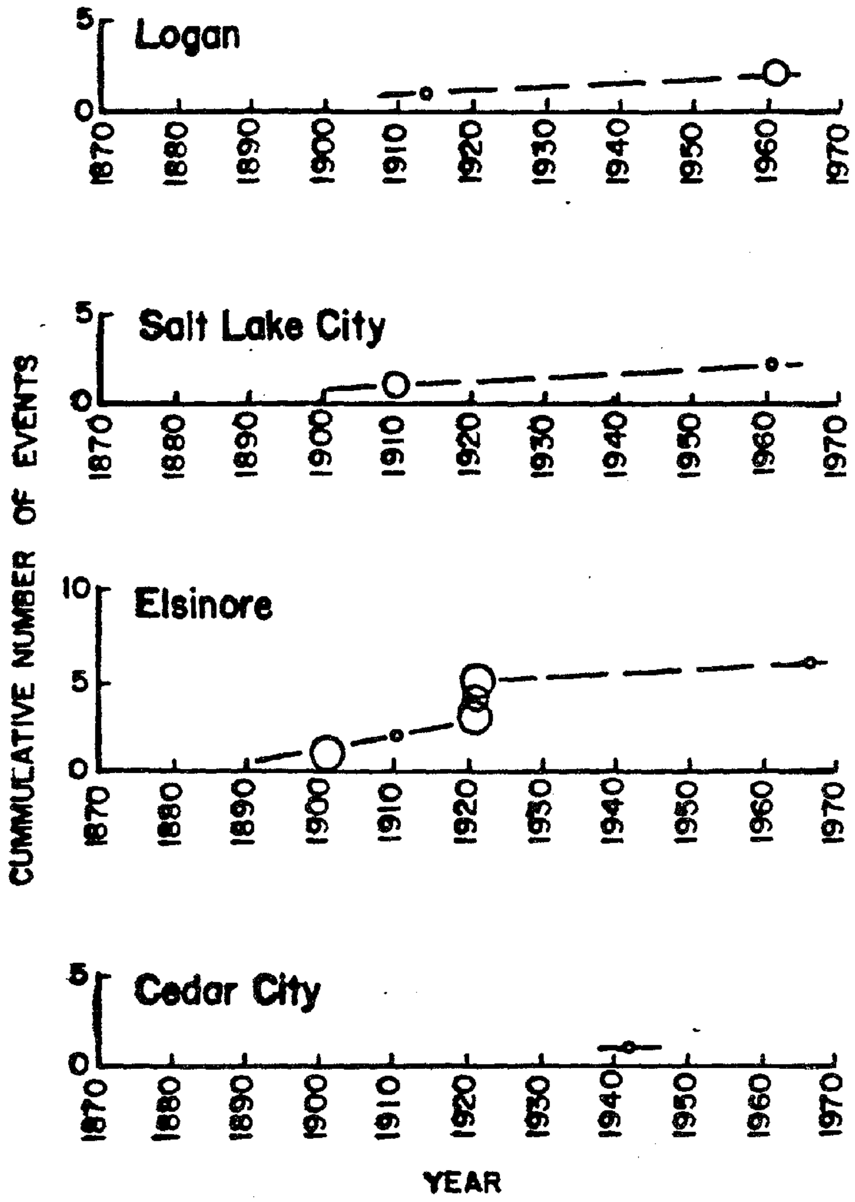

Fig. 30 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN UTAH AND SOUTHEASTERN IDAHO.

can be justified in this region. In view of the probability that a major event will occur in the future, even though the time of its occurrence can not be predicted, and in order to obtain at least one record from any magnitude 6 or greater event, twelve accelerographs should be located in this region as indicated in Figure 31.

The locations of the existing accelerographs in this region are also indicated in Figure 31. The older instrument at Logan should be replaced when the remainder of the network is established. The existing installation at Salt Lake City is in the VA Hospital where there is one instrument in the basement and one at the roof level. The instrument at Flaming Gorge is near a major dam, although the dam itself is not instrumented. In view of the projection of a low rate of return of strong-motion data in the near future, no additional installations in this region are recommended.

As a supplement to these accelerographs and in view of the probability that a major event or a sequence of major events will occur in this region in the future, additional instrument stations could be established. These stations should be planned so that accelerographs could be installed rapidly if there were indications that a major event is in the offing or for aftershock studies if a major event occurs with little warning. In the meantime, seismoscopes could be installed at these sites so that at least some record would be obtained if a major event were to occur.

A careful study of the trends indicated by microearthquake activity in the region could aid in future planning of a strong-motion program for this region. This may require an extension of the existing teleseismic network in Utah to include areas of southern Nevada and northern Arizona.

Colorada, New Mexico, and Oklahoma

Figure 2 indicates that there are concentrations of activity near

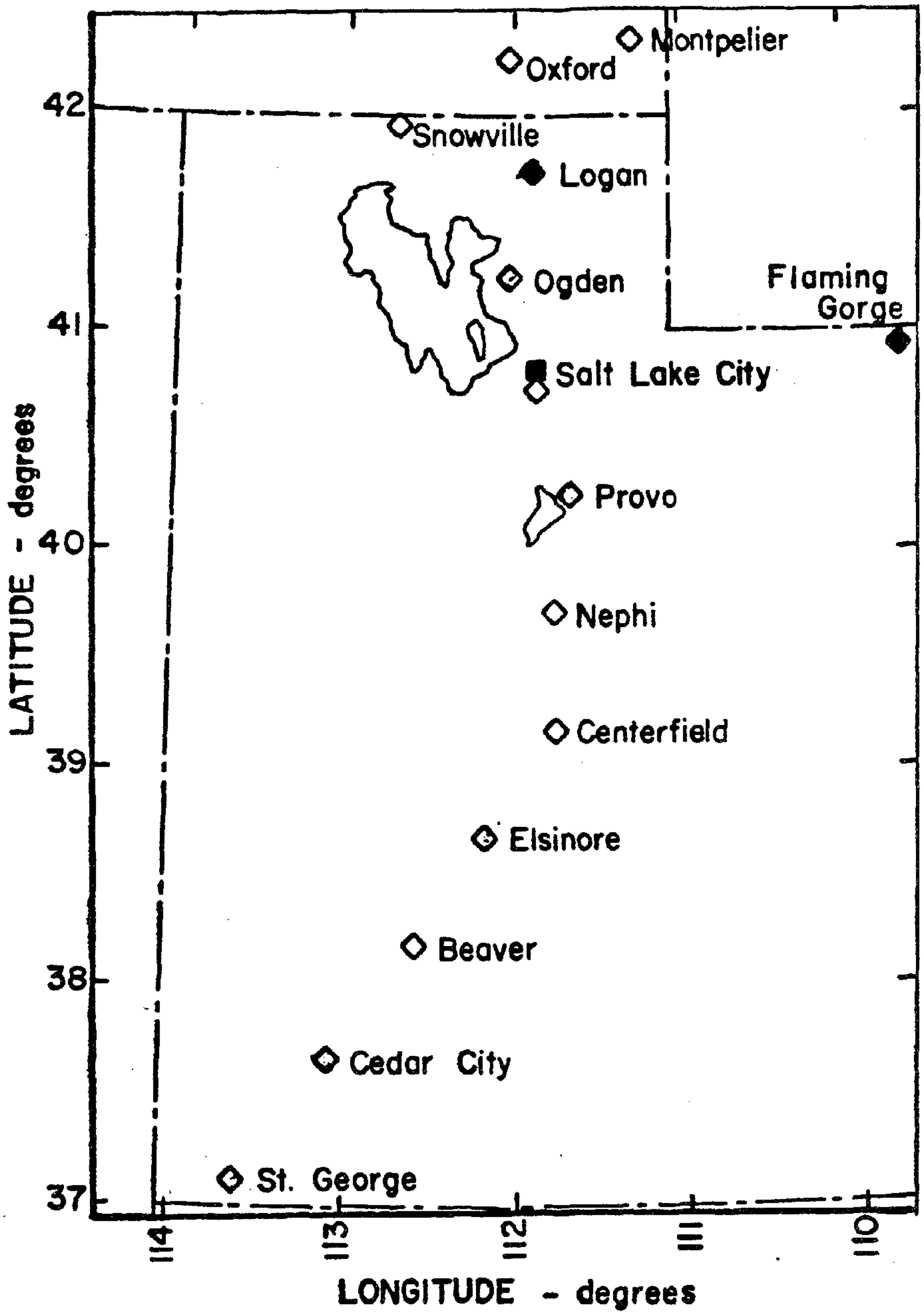

FIGURE 31 - STRONG-MOTION ACCELEROGRAPH SITES IN UTAH. SOLID SYMBOLS INDICATE EXISTING STATIONS. OPEN SYMBOLS INDICATE PROPOSED STATIONS. ◇ GROUND STATIONS □ BUILDING INSTALLATION

Denver, Colorado; El Reno, Oklahoma; and from Santa Fe to Socorro, New Mexico. Plots of the activity in these areas were prepared in the same manner as illustrated above for other regions. The results indicate that none of these areas can be considered active from the standpoint of recurring strong ground motions at any individual site.

The activity near Denver started in 1962 and ended in 1967. It appears to have been associated with the fluid injection at the Rocky Mountain Arsenal (Raleigh and others, 1976) and is not likely to resume. Two dams in the area are instrumented and this instrumentation is probably adequate unless there is some indication of an increase in activity.

The strong-motion activity in Oklahoma is concentrated near El Reno, Oklahoma, with some minor activity to the south and east. The historical events for which significant strong ground motions could have been recorded at El Reno consist of one event in 1929 and three events in the early 1950's. Small events are still reported in the area. Accelerographs are located at the Oklahoma City VA Hospital, at Kaw Dam in Oklahoma, and at Tuttle Creek Dam in Kansas. This is probably adequate instrumentation in this region unless there is some indication of increased activity.

The activity in New Mexico is distributed between Santa Fe and Socorro with some activity dispersed in an undefinable manner throughout the state. The historical record indicates that the concentration of strong-motion activity west of Socorro and south of Magdelena began in 1869 and ended in 1907 and that the activity between Santa Fe and Socorro is dispersed in time as well as space. At the present time, accelerographs are installed at Cochiti Dam near Santa Fe and at the VA Hospital at Albuquerque. Because of the continuing microearthquake activity between Albuquerque and Socorro, it may be desirable to install an additional accelerograph at Socorro or

Magdelena and a line of seismoscopes from Socorro to Santa Fe. The faulting in this region indicates that major events have occurred in the past, so that the microearthquake activity in this region should be studied for indications of possible future strong-motion activity.

Mississippi Valley

The distribution of historic strong-motion activity in the Mississippi Valley is shown in Figure 32. The main area of activity is along a line from Blytheville, Arkansas to Cairo, Illinois. This corresponds to the epicentral region of the 1811-1812 New Madrid earthquakes. Secondary areas of activity extend from New Madrid west and north as far as St Louis and northeast to Vincennes on the Wabash River. The interrelationships, if any, among the three subregions of activity is not clear. The historic pattern of activity in the New Madrid area is reflected in the recent pattern of microearthquake activity, as shown in Figure 33 (Stauder and others, 1977). The historic pattern of activity and the recent microearthquake activity also correlate with recent observations of fault patterns in the Mississippi embayment by McKeown and others (O'Leary, 1977).

The projected histories of possible recording of significant strong ground motions for particular sites in the Mississippi Valley are shown in Figures 34 and 35. At New Madrid and Charleston, in the area of highest activity, a reasonably uniform rate of possible strong-motion recording is indicated. For sites somewhat removed from this area, the projected histories appear to have come from a few isolated events or from a series of events all of which occurred during a limited period of time. The rates of activity at New Madrid and Charleston are comparable to those for sites along the Hayward fault or in the Transverse Ranges in California, but a review of

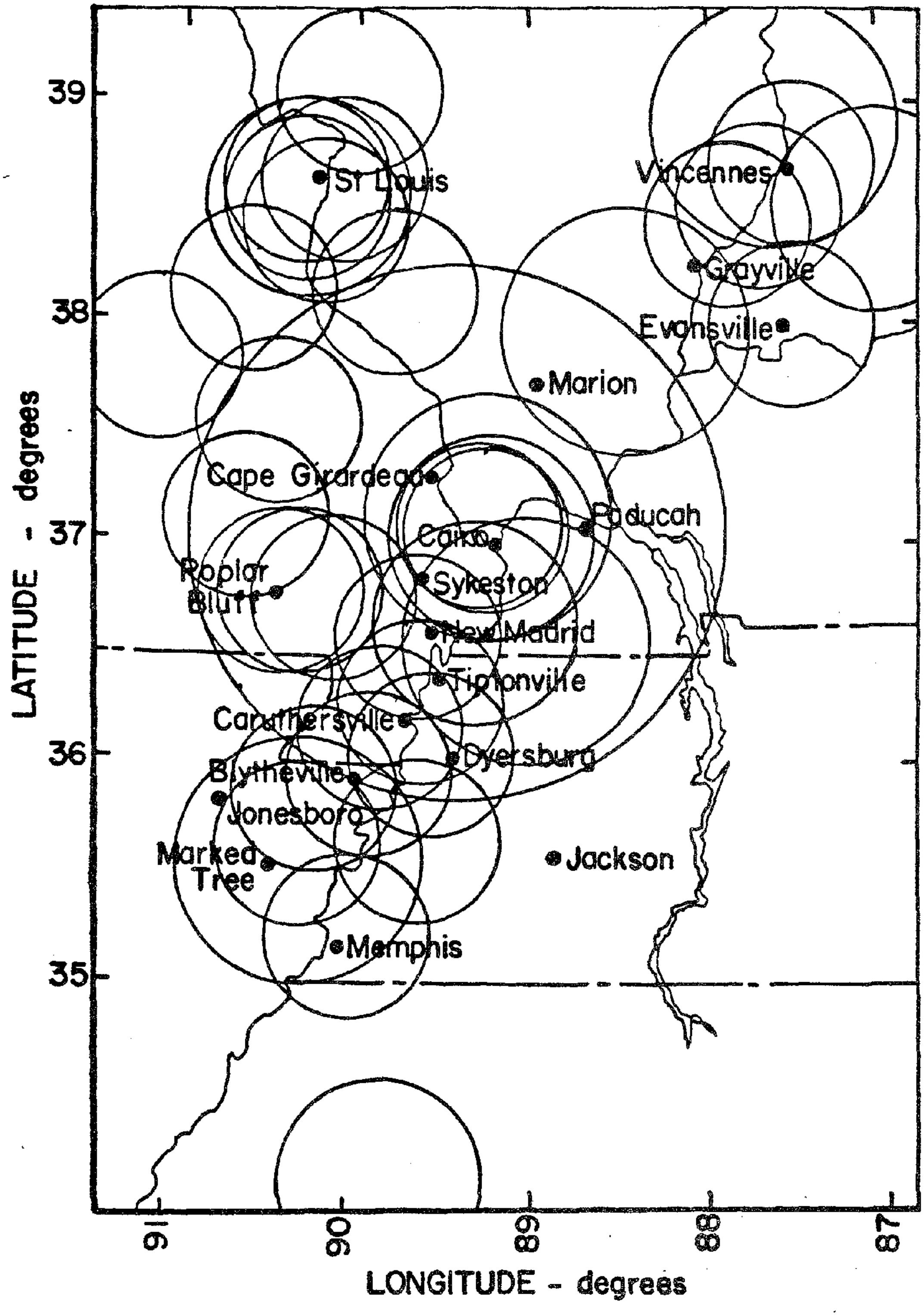

Fig. 32 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN THE MISSISSIPPI VALLEY, 1870 - 1970.

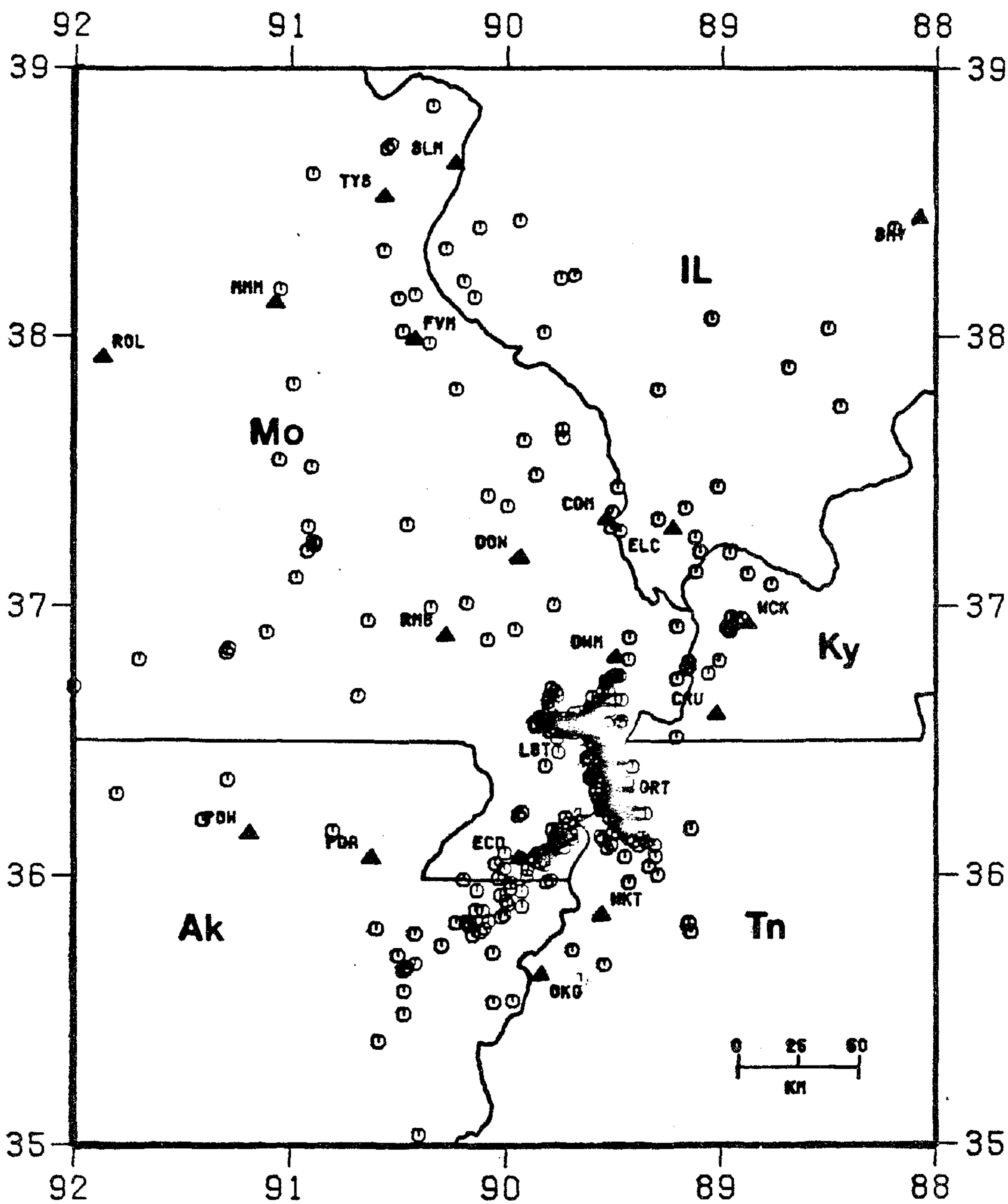

Fig. 33 - CUMULATIVE EVENTS 29 JUN 1974 TO 31 DEC 1976
LEGEND . ▲ STATION ⊙ EPICENTER
(STAUDER AND OTHERS, 1977).

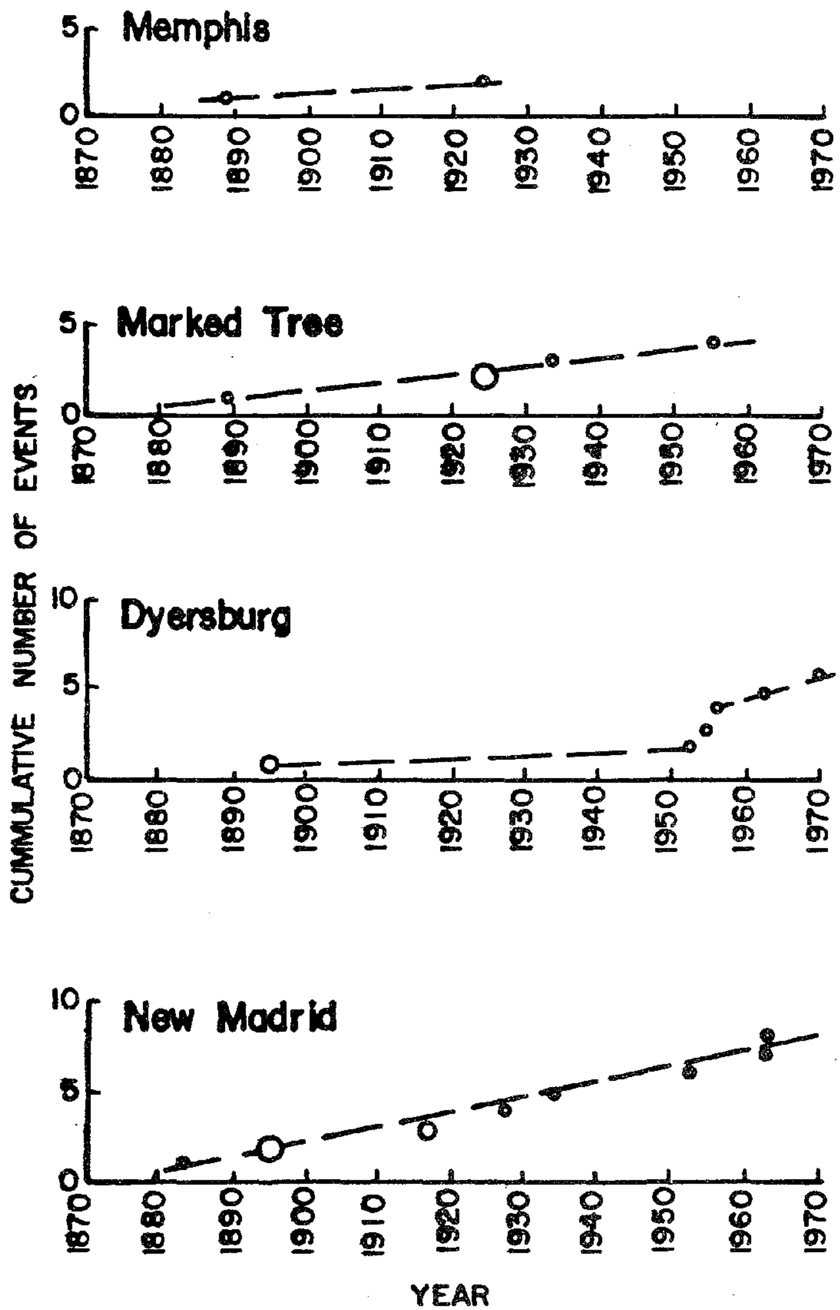

Fig. 34. - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN THE MISSISSIPPI VALLEY.

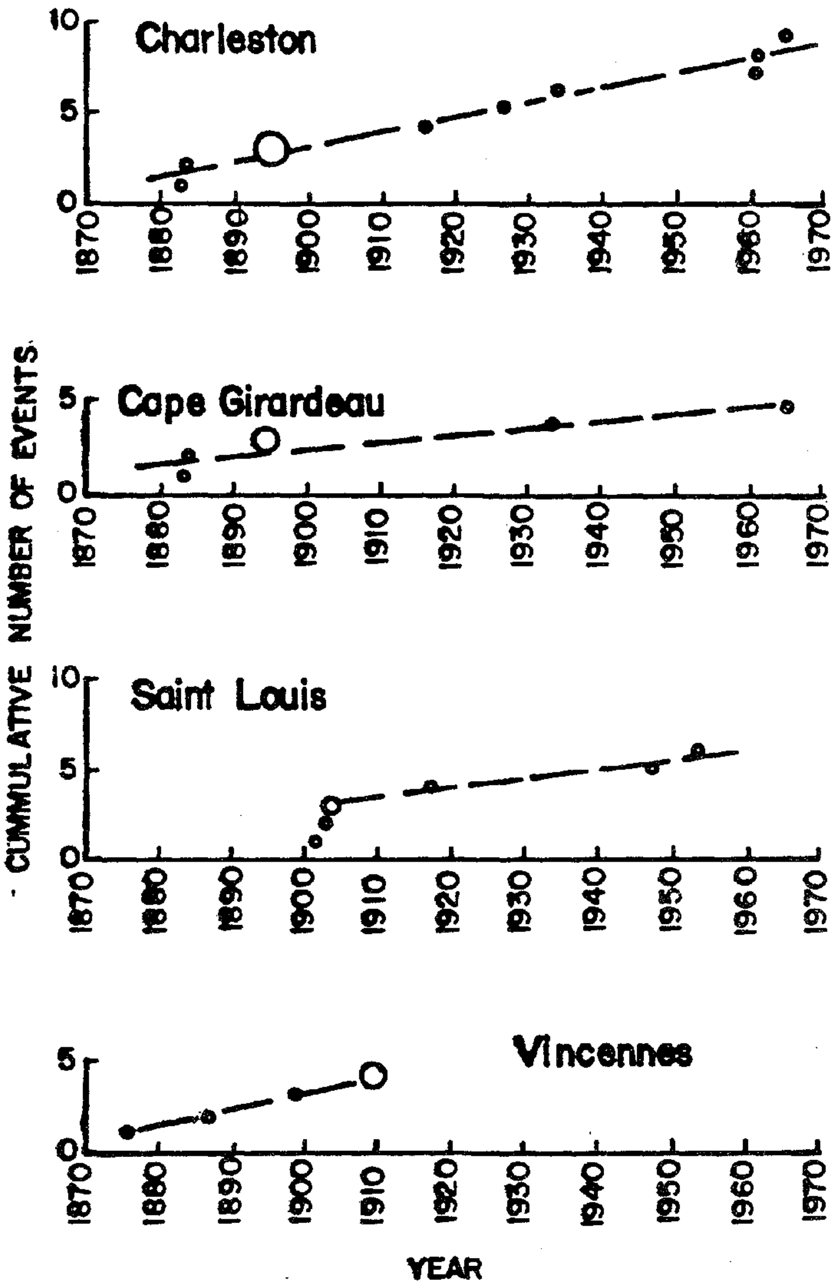

Fig. 35 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN THE MISSISSIPPI VALLEY.

the temporal distribution of the events classified by maximum intensity suggested that the present activity may be the "tail" of the aftershocks of the 1811-1812 New Madrid earthquakes.

Because of the importance of quantifying the differences in the attenuation of motion in this region compared to that in California, the comparable rates of return imply that a similar effort should be expended in the area near New Madrid as is being expended in the areas of comparable activity in California. The area in which the level of recent activity is sufficient to justify a dense network of instruments extends from the Missouri-Arkansas border to Cairo, Illinois. A network of surface instruments with a spacing of 20 km appears to be appropriate within this area. A closer spacing may not be needed in view of the relatively simple model of the near-surface geology that is anticipated and in view of the lower attenuation rate in this region as compared to regions in the west. Outside of this area, the return of data would be expected to be lower, but the data on ground motions in this region is sufficiently important that the network should be extended (with increased spacing) to cover the entire area of potential activity.

A possible network of instruments to measure ground motions is illustrated in Figure 36. In the central portion, a spacing of about 20 km is indicated, whereas in the outer portion, the spacing may be extended to 40 km. Beyond the region in which recent activity indicates that a minimum level of return of data is possible, seismoscopes might be used rather than accelerographs. These simpler instruments would be used out to the limit at which strong-motion data would be desired from a major event. This network of instrument stations should provide data on the regional characteristics of the ground motion in the area, but may not provide information on soil failure from liquefaction which is to be anticipated in the area along the

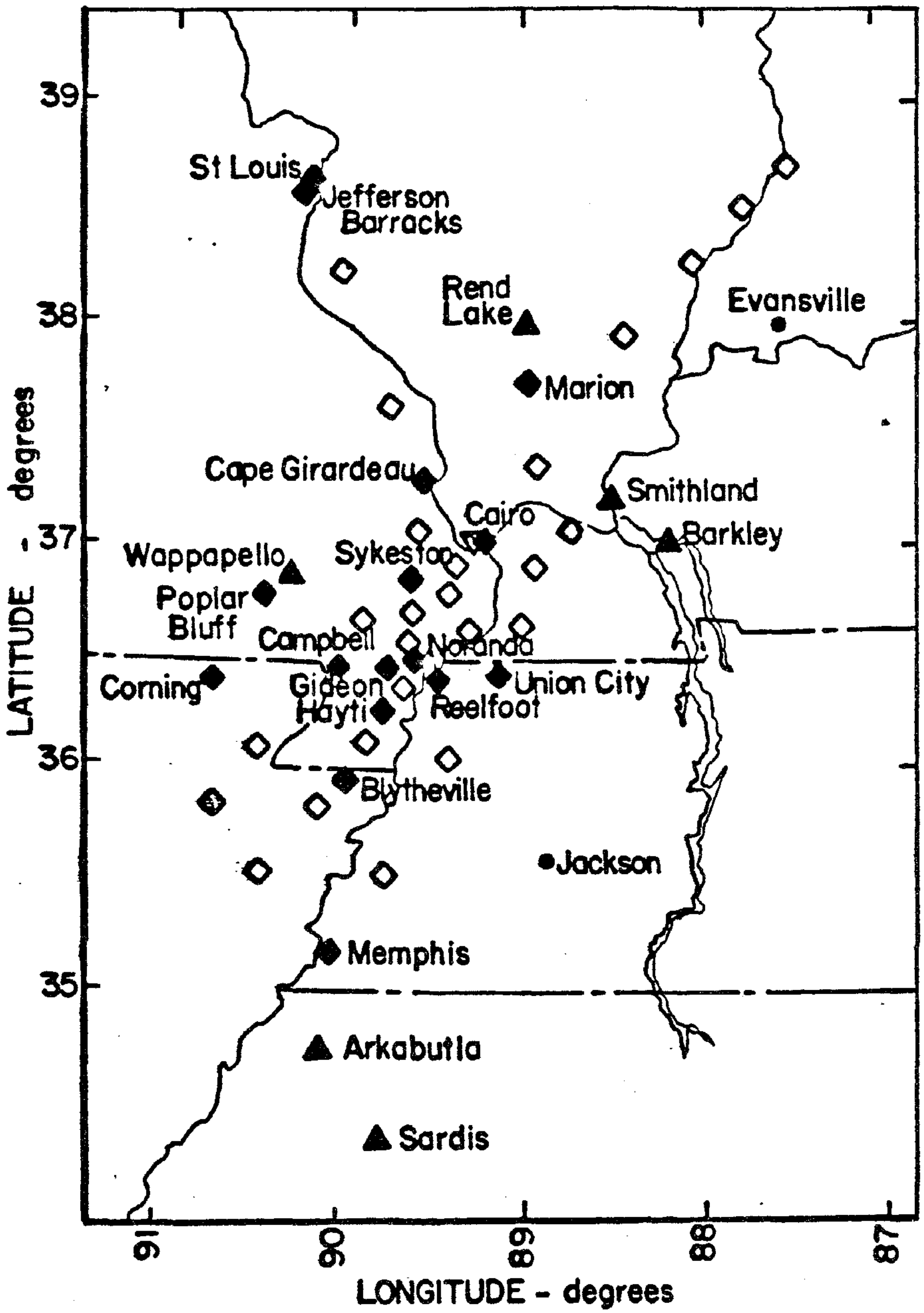

Fig. 36 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE MISSISSIPPI VALLEY REGION. ◆ GROUND STATIONS, ▲ DAMS.

Mississippi River. To obtain data of this type, additional accelerographs may be required at several sites near the river.

Cursory inspections were made in an attempt to identify representative structures that would be candidates for instrumentation. Within the area of highest current activity, no suitable structures were found, but beyond the area of highest current activity, there are several candidate buildings. These are located in the towns of Poplar Bluff and Cape Girardeau, Missouri; Anna, Illinois; Paducah, Kentucky; and Memphis, Tennessee. Wappapello dam is the closest dam to the region of highest activity. This dam in Missouri and Sardis and Arkabutla in Mississippi, Rend Lake in Illinois, and Barkley in Kentucky have been instrumented by the Corps of Engineers. The level of instrumentation provided on these dams appears to be adequate in view of the anticipated levels of strong-motion activity at each of the sites, which are some distance from the area of current activity. One bridge that is a potential candidate for instrumentation was recently constructed on Interstate Route 57 near Cairo, Illinois, and discussions are underway with the Federal Highway Adminstration (FHWA) concerning instrumentation of that bridge. The levees along the river are important embankment structures that could suffer from liquefaction of the supporting material or from failures in the embankment materials during a major earthquake. Instrumentation should be placed on some of the levees in the vicinity of New Madrid.

Ohio

A small area of activity occurs at Anna, Ohio, as indicated in Figure 2. This activity is of limited spatial dispersion, and ground motions with amplitudes above the threshold level could have been recorded during the period from 1875 to 1885 and from 1930 to 1940, only. Although there is persistent microearthquake activity, the 45-year period when no significant strong ground motions could have been recorded implies that only a minimum number of strong-motion instruments can be justified.

Accelerographs have been installed at the VA hospitals in Dayton, Ohio and Marion, Indiana. One additional accelerograph should be installed at Anna. Ten seismoscopes have been loaned to the University of Michigan for installation in the immediate vicinity of Anna. These sites should be prepared so that accelerographs may be installed rapidly if the microearthquake activity indicates a possible buildup to another sequence of moderate-sized earthquakes.

East Coast

Along the east coast there are several "spots" of activity as indicated in Figure 2 and a few major historical earthquakes as indicated in Figure 3. A detailed review of the distribution of activity in each of these areas was conducted, but this did not lead to increased insight over that which can be surmised from Figures 2 and 3.

No more than two strong-motion records could have been obtained at any one site near Attica, New York in the 100-year period considered. Accelerographs are installed in the VA hospitals at Buffalo, Batavia, and Canandauga New York and at Mount Morris Dam, all in the general vicinity of the historic activity near Attica. This appears to be sufficient instrumentation in this region considering the probable rate of return of data from stations in this region.

In New England, only a few sites would have experienced strong ground motions in the 100-year period from 1870 to 1970 and no site would have experienced more than two strong motion events. During that period there was less than a 35 percent chance that strong motions above the threshold level could have been measured at at any arbitrarily selected site in the "Boston to Ottawa corridor". The accelerographs that are installed at MIT, at the four VA hospitals in the Boston area, at two Corps of Engineers dams in the area, at a FHWA bridge near Massena, New York and at four sites in the Montreal-Ottawa area of Canada provide considerable instrumentation in this region. Additional instruments are scheduled to be installed at several dams in the area in the near future.

At Arvonia, Virginia all of the strong-motion activity occurred prior to 1910, and there is no indication that a strong earthquake will occur again. No accelerographs are installed in the vicinity of this historic activity, and no more than one could be justified.

The history of strong-motion activity in Giles County, Virginia suggests that small to moderate events may occur there at intervals of 60 years, or so. Accelerographs are installed at the VA hospital at Salem and at Gaithwright dam in Virginia, and this appears to be adequate instrumentation in the area in view of the low level of activity.

The history of strong-motion activity in the Asheville-Oteen, North Carolina area indicates that since 1916 there has been a relatively uniform rate of return of MMI = VI events with a return period of from 10 to 15 years. Is the history prior to 1916 incomplete, or is this a buildup to a major event? Will a large event ever occur? The extent of the region in which strong-motion records could have been obtained is very limited. An accelerograph is installed at the VA Hospital at Oteen, North Carolina, and additional instrumentation in this region does not appear to be justified at this time.

The activity near Charleston, South Carolina consists of the 1886 earthquake and its aftershocks. Will the event ever be repeated? Although low-level activity is continuing today, only one "strong-motion" event could have been recorded since the Charleston earthquake of 1886 and its immediate aftershocks. Two accelerographs are installed at the VA Hospital in Charleston and accelerographs are scheduled for installation at Summerville and Middleton Gardens, South Carolina near the epicenter of the 1886 event, a region of continuing low-amplitude activity. In addition, accelerographs are installed at several other facilities throughout South Carolina.

Puerto Rico

The activity near Puerto Rico generally is to the north and west of the island. A review of the history of strong-motion activity at the west end of the island indicated that strong ground motions could have been recorded only in 1911 and 1924. The existing network of 8 strong-motion accelerographs on the island is believed to be adequate to monitor the ground motions that might occur in the near future. Additional instruments might be installed at the three dams in the northwest portion of the island if more coverage is desired.

Hawaii

The distribution of historic strong-motion activity in the Hawaiian Islands is shown in Figure 37. The activity is concentrated near the main island of Hawaii, and much of it is associated with the active volcanos on that island. On the other hand, major faults have been identified in the channels between the islands and on the main island (Furimoto and others, 1972).

The projected histories of possible strong-motion recording at several sites on the main island are shown in Figure 38. These projected histories

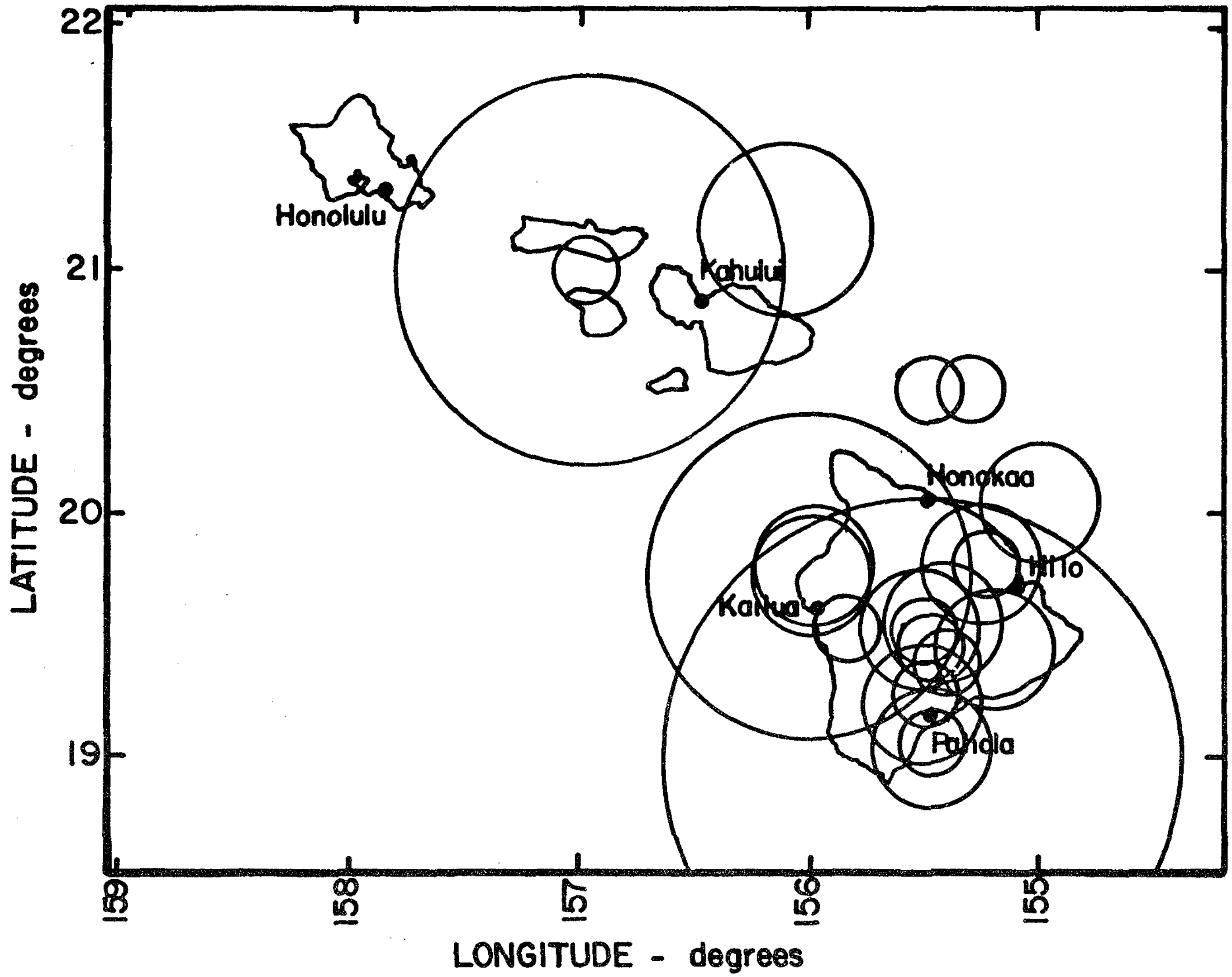

Fig. 37 - MODIFIED MERCALLI VI OR GREATER EARTHQUAKES IN THE HAWAIIAN ISLANDS, 1870 - 1970.

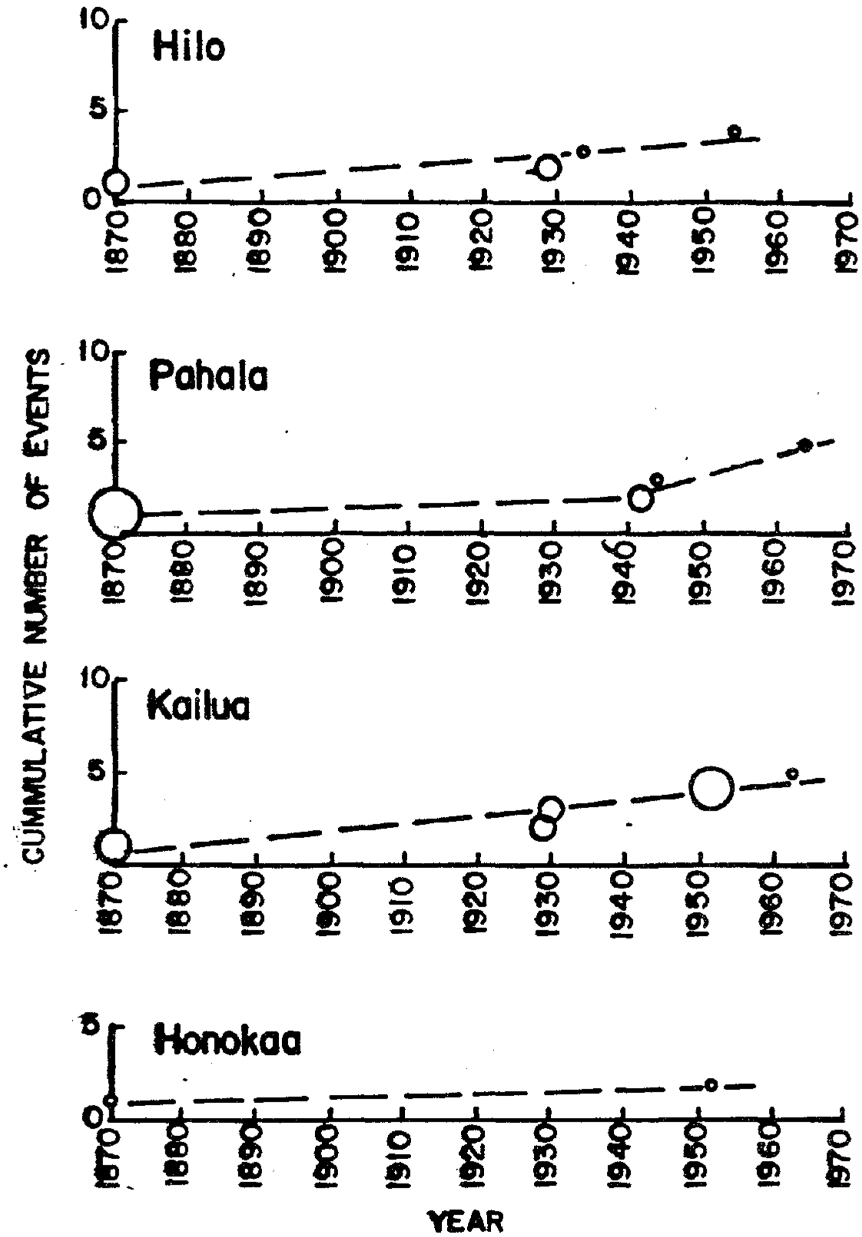

Fig. 38 - PROJECTED HISTORIES OF STRONG-MOTION RECORDING FOR STATIONS IN THE HAWAIIAN ISLANDS.

suggest that either the historical record is incomplete prior to 1930 or the 1868 event relieved the state of stress, which resulted in a 62-year period when no strong ground motions could have been recorded. The current rates of activity on the island of Hawaii are as high as those in many of the active areas of California.

Strong-motion accelerographs were first installed on the Island of Hawaii in 1972, and records were obtained from earthquakes in 1973 and 1975. In both cases, the number of instruments that recorded the event was insufficient to provide the data necessary to adequately interpret the pattern of ground motion. Because of the relatively high activity on the Island of Hawaii, an expanded network of instruments for measuring ground motion is proposed. The locations of the existing and proposed instruments are shown in Figure 39. This instrumentation provides a reasonably uniform spacing of instruments around the island, where sites are known to be accessible. An on-site investigation must be made before proposing to install instruments in the interior of the island. In addition, instruments should be installed in two representative buildings in Hilo, and an accelerograph should be installed on each of the Islands of Maui, Molokai, and Oahu.

Alaska

The historical record of earthquakes in Alaska as summarized by Coffman and von Hake appears to be incomplete even for relatively recent times. This is the result of the sparse distribution of population in Alaska and the consequently sparse distribution of intensity reports. On the other hand, the character and distribution of major earthquakes in Alaska is relatively well known from the geology and the instrumentally recorded seismicity. The distribution of earthquakes with magnitudes greater than or equal to 6 are shown in Figure 40 (C&GS, 1966).

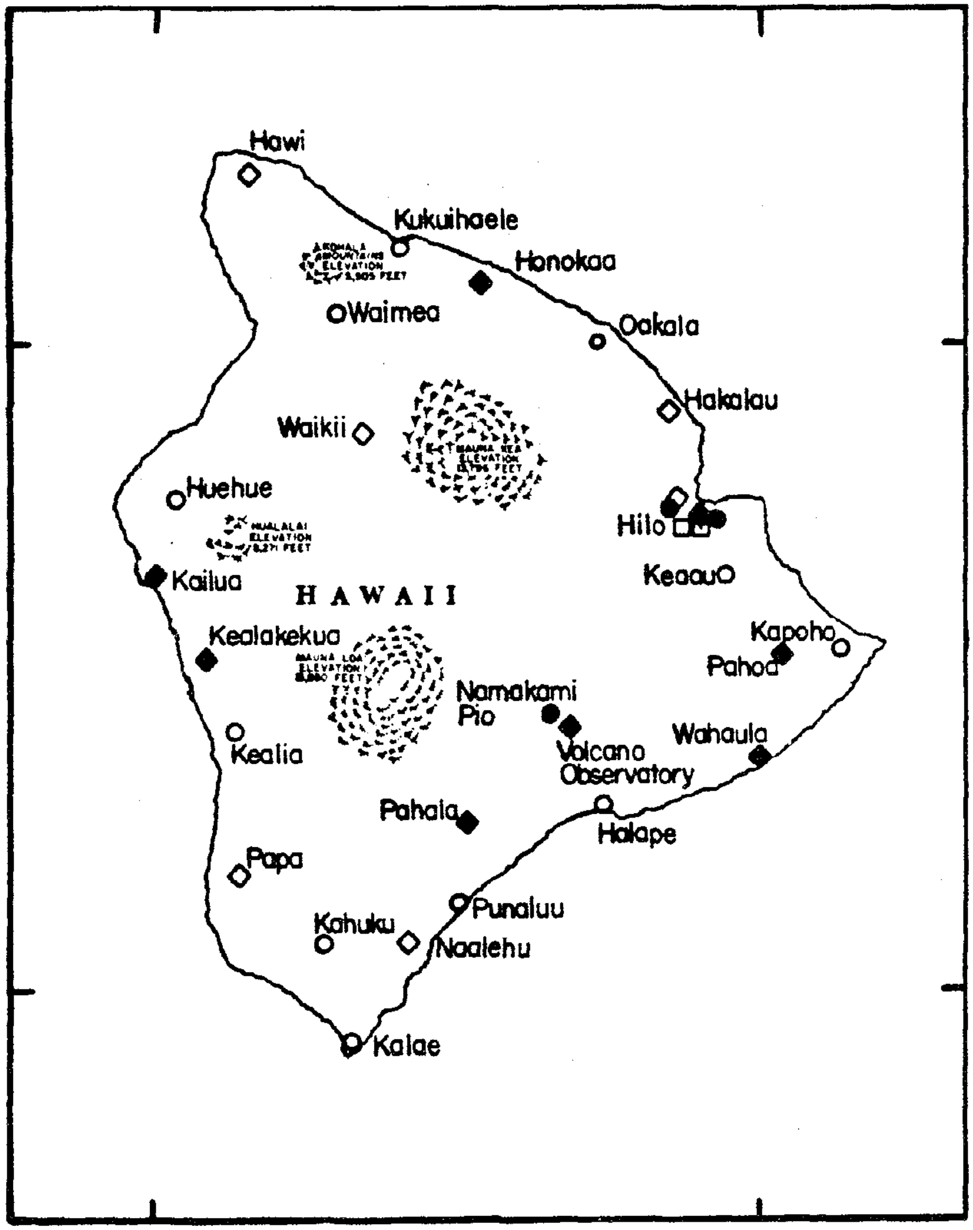

Fig. 39 - STRONG-MOTION ACCELEROGRAPH STATIONS IN THE HAWAIIAN ISLANDS.
◆ GROUND STATIONS, □ BUILDINGS, ○ SEISMOSCOPES.

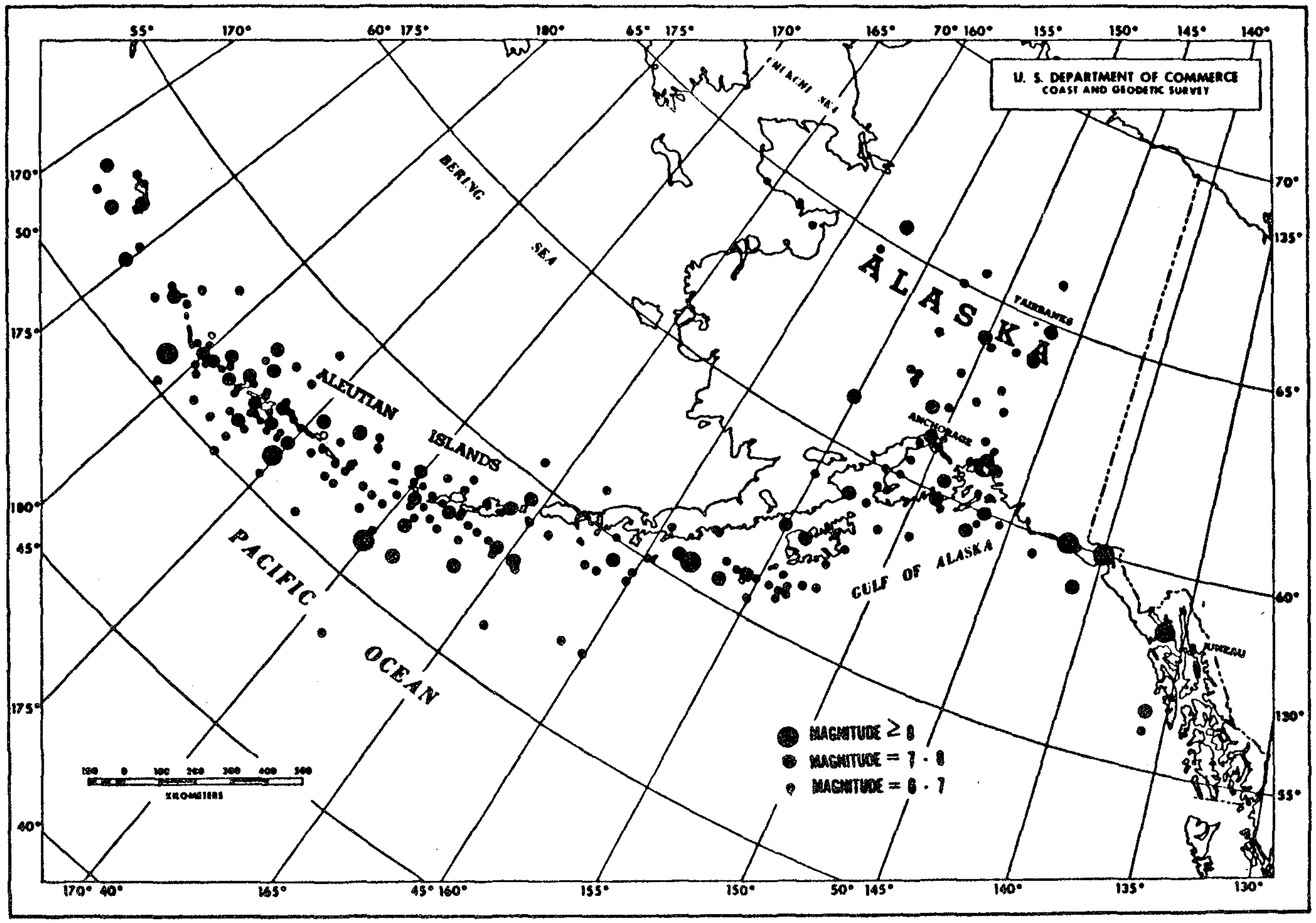

Fig. 40 - EPICENTERS OF MAGNITUDE 6 OR GREATER EARTHQUAKES IN ALASKA. (C&GS, 1966)

A recent analysis of the seismotectonic framework of Alaska has identified 25 source areas with distinctive geologic conditions and earthquake potential (Ziony, personnal comm.) Earthquake source areas likely to produce relatively frequent large to great events are associated with segments of the subduction zone of the Aleutian trench and island arc. An interlacing system of source areas is associated with strands of the Denali, Lake Clark, Fairweather, and Chatham Strait faults. A broad area with potential for large shallow earthquakes is identified with a series of faults between the Denali fault and the Yukon River; the largest historic event north of the subduction zone (the magnitude 7.7 earthquake of 1904) was associated with this area. The remaining source areas that have been identified are not considered to be significant relative to the planning of a strong-motion network.

Logistical problems have caused several of the stations that had been installed in Alaska to be abandoned, so that accessibility of the site for instrument maintenance has to be a primary criteria in selecting additional sites in Alaska. Furthermore, the configuration of the land forms in the Aleutian Islands and the Alaskan Peninsula relative to the region of highest seismicity do not permit suitable arrays for detailed studies of ground motions to be planned. On the other hand, this may be the region of the U.S. in which there is the greatest likelihood of obtaining data from a magnitude 7.5 or greater earthquake. The locations of the existing instruments in Alaska are shown in Figure 41. Because of the relatively high level of activity in Alaska, some additional instruments might be installed at accessible sites along the Gulf of Alaska and in the Aleutian Islands. The instrumentation currently in buildings in Anchorage should be upgraded to current standards, and critical structures such as Eklutna dam should be instrumented.

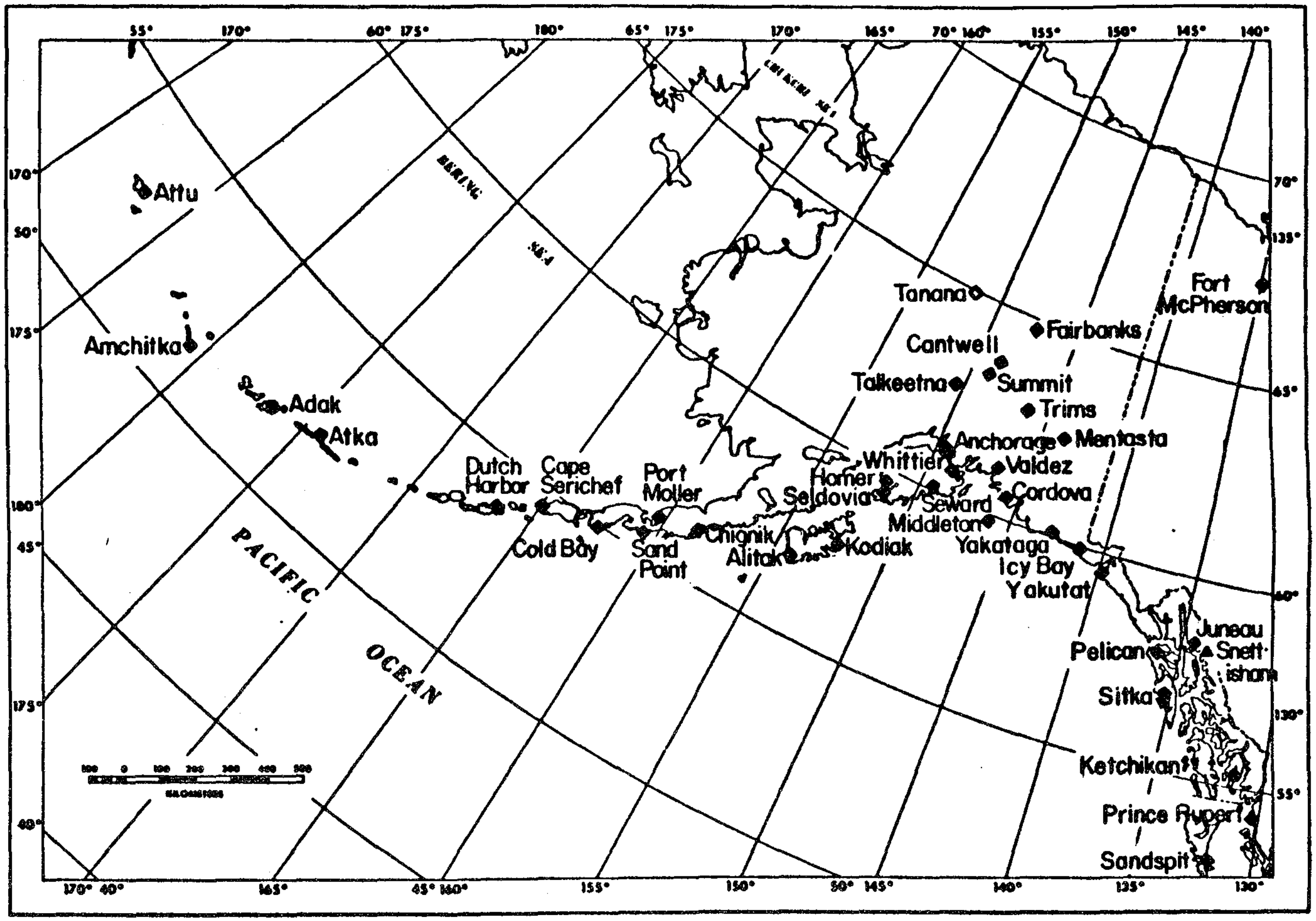

Fig. 41 - STRONG-MOTION ACCELEROGRAPH STATIONS IN ALASKA.

PRIORITIES AND IMPLICATIONS

To establish engineering design criteria and to evaluate earthquake hazards, studies of the spectral characteristics of strong ground motion, of regional differences in these characteristics and of the spectral attenuation are the most important topics for which additional strong-motion data are required. An assessment of whether this data can be obtained from aftershock studies needs to be made. Studies of the inelastic response of structures and of the influence of soil-structure interaction on such response are probably the second most important type of strong-motion studies relative to engineering research and design applications. Studies of local site effects (amplification effects resulting from soft surficial layers, or differences in motion at nearby points on the ground surface), and of soil failure phenomenon (liquefaction or landslides) are of lesser importance, but they are sufficiently important that special arrays should be placed in several regions where the potential for soil failure is recognized and where a high rate of return of sufficiently strong ground motions are likely. On the other hand, the combination of a reasonable rate of return of ground motions at high enough levels of motion with the soil conditions necessary for soil failures to occur or with structures suitable for studying inelastic response may not exist. Few such sites were identified during the cursory inspections conducted after completion of the preliminary planning study.

From the discussion of strong-motion activity in each region of the country, it may be seen that special ground motion and structural response studies should be planned for the Cape Mendocino area, along the Hayward fault, in the Gilroy to Hollister area, in the Transverse Ranges, and in the Imperial Valley of California. Outside of California there are few regions in which research type studies of structural response can be justified based on the anticipated return of data. Regions in which the development of networks to study ground motion may be justified based on the potential return of data are the Mississippi Valley and the Island of Hawaii. Along the shore of the Gulf of Alaska and in the Aleutian Island arc is an area of considerable activity, but the logistical problems of maintaining instruments and the locations of the islands relative to the sources of major earthquakes impose additional constraints which dictate that only a minimum network of instruments for ground motion studies be developed in this region. Western Nevada and the Puget Sound trough are regions in which major events have occurred in the recent past, but the uncertainty regarding the level of current activity precludes the development of more than a minimum network of ground stations in these regions. The Honey Lake and Long Valley areas in California and the Flathead Lake area in Montana are areas in which a buildup of activity may be occurring that could lead to a major earthquake at sometime in the near future. This activity must be monitored and plans should be made to respond to any indication that a major event is likely to occur. The regions in which instruments should be installed to monitor critical structures, such as dams and nuclear power plants, clearly include many of the regions that are of relatively low priority for research type studies. The regions of highest priority for monitoring the response of critical structures are those within the "boxes" in Figure 2. Structures in the regions adjacent to the "boxes" should be considered as candidates for instrumentation but additional criteria must be considered in selecting such structures. In all other areas, the level of strong-motion activity is so low that no permanent networks can be justified. To supplement the network of permanently installed strong-motion instruments, other instruments should be maintained in a stand-by condition at several locations for rapid deployment in the study of ground motions from aftershocks.

In the attempt to select structures that might be suitable candidates for instrumentation, it was found that very few are located in regions in which a short return period could be expected. As a result, the question of how the information that is desired can best be obtained in a reasonable time must be readdressed. A possible alternative to the use of existing buildings or those under construction is to build "half-sized" structures that have been designed to the conditions that are expected to occur within the next ten years at a site in a relatively active area. The concept would be to "underdesign" the structures relative to current practice. They would be designed to undergo inelastic deformations for the levels of ground motion that are expected to occur with a ninety percent confidence, for example, in the next ten years. Obviously if a greater level of motion were to occur in that time, then more severe damage would occur, possibly leading to total collapse. The information obtained, however, would be of great value as a basis for improved understanding of the response of actual buildings and for improved design practice to resist such damage. Suitable sites could be selected in the Imperial Valley, in the Hollister area, and in the Cape Mendocino region of California. These regions have the highest activity (shortest return period); they are relatively rural in demography; different soil conditions are present; and they present few logistical problems. This concept of instrumenting "underdesigned" structures could be applied to other structures as well. As an extreme example, "typical" offshore structures could be built off Cape Mendocino to evaluate the design of such structures.

The preceding discussion of concepts and plans for development of a national network of strong-motion instrumentation is thought to be in line with the current constraints on manpower and funding. No attempt has been made to indicate the agencies responsible for the development of various portions of the network, but it is assumed that the major burden for development of a basic research network rests with NSF and the CSMIP and that the current cooperative programs with agencies primarily concerned with operations will continue. The importance of adequate strong-motion data to the fields of Geophysics, Seismology, and Earthquake Engineering places some urgency on the development of the network, but the inherent long term nature of the process of gathering strong-motion data places the burden on the present generation to plan wisely for future generations who will utilize the data in research, design, operations, and regulation.

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