Location and Real-time Detection of Microearthquakes Along the San Andreas Fault System in Central California *

S. W. STEWART, W. H. K. LEE and J. P. EATON
U.S. Geological Survey, National Center for Earthquake Research,
Menlo Park, California

Abstract

A network of more than 50 seismograph stations is operated in central California by the National Center for Earthquake Research to study microearthquakes along the San Andreas and related fault systems. Spacing of the stations ranges from five to 30km, and the network covers an area approximately 75km by 300km. Each station contains a short-period vertical-component seismometer, and seismic data are telemetered to a central recording centre at Menlo Park. This dense network of telemetered stations permits the precise location of earthquakes with magnitude about zero or greater.

Seismic data are recorded on 16mm film and on analog magnetic tape. A recent addition to the data processing capability is a high-speed digital computer capable of accepting up to 32 analog seismic channels as input. An algorithm has been programmed for the computer to detect local seismic events in real-time and to discriminate against transient noise and teleseisms. P-phase onset times and maximum amplitudes are output automatically by the computer within 30 seconds after the occurrence of a local earthquake. Onset times as determined automatically and by hand differ less than 0.1 second for most impulsive events.

Results for the 19-month period ending September 1969 (with about 2,000 earthquakes located) show that (1) almost all earthquakes occur in narrow, nearly vertical zones of shallow depth (<15km) along the San Andreas fault system, and (2) the most active region is near the town of Hollister where much of the microearthquake and fault creep activity seems to be transferred from the main San Andreas fault to its subsidiary branches.

INTRODUCTION

THE San Andreas fault system in central California is the locus of many phenomena associated with currently or recently active geologic processes. The main seismic and deformational features of this region can now be described in moderate detail. With the advent of the new global tectonics (Isacks and others, 1968), the San Andreas fault system is cast in a new light: it can be regarded as a transform fault system between the spreading centre associated with the East Pacific Rise and either the Gorda and Juan De Fuca Ridges or the Aleutian Trench. As a transform fault system the San Andreas is particularly amenable to study because for most of its length it is situated well inland within California. Details of the transform system, particularly with regard to the nature of the termini, are still to be worked out.

In 1966 the U.S. Geological Survey's National Center for Earthquake Research (NCER) began a programme to study selected portions of the San Andreas fault system with particular emphasis on the central California Coast Ranges region. Programmes appropriate to studies of current microseismicity and ground deformation were started. These programmes were in addition to the long-continuing programmes of geologic and seismic studies in the region by this and other institutions.

At present several telemetry networks consisting of approximately 100 short-period seismic stations are maintained by NCER in various regions of the western USA. The output of each seismometer is telemetered continuously to NCER offices in Menlo Park and recorded along with a standard broadcast time signal. Nearly all seismic telemetry is via voice grade telephone lines, although radio telemetry exists and is operational for a few stations. The standard mode of recording is on 16mm film, approximately 14 stations and two timing channels to a film. Recording is also done on analog magnetic tape.

Since January 1968 a network of more than 30 seismograph stations in the central California region has been maintained by NCER. At present the network consists of about 50 stations and defines a rectangular region about 75km by 300km. The long dimension of the rectangle is approximately parallel to the NW strike of the San Andreas fault, and extends from San Francisco 300km south-east to Cholame, historically the site of many earthquakes of intermediate size (Brown and others, 1967). The network of telemetry stations is most dense in the central portion, near the junction of the San Andreas fault with the Hayward and Calaveras faults, and is less dense to the north-west and south-east. The network records locatable microearthquakes, some with magnitudes less than zero, at the rate of a few thousand per year. Eaton and others (1970) summarise results of some microearthquake studies in this region.

In addition to the results of the microearthquake studies themselves, there has been increased interest in the prospects for computer-based, automatic detection and processing of local seismic events. Interest has been stimulated by (1) the establishment of relatively large seismic telemetry arrays to study local earthquakes or aftershock sequences in currently active tectonic or volcanic regions, (2) the large amounts of data generated by such arrays, (3) the ready availability of computer equipment appropriate to the problem, and (4) the prospects for conducting active field experiments in which it may be necessary to monitor microearthquake or aftershock activity on a minute-by-minute basis. In order to establish the feasibility of real-time earthquake detection and processing, a CDC-1700 digital computer system was added to the NCER research programme in 1969. The computer system is relatively small, but oriented towards high-speed real-time operation with fairly high data acquisition rates. At the present time 32 analog signals from the telemetry lines, or from magnetic tape, may be input directly into the computer for simultaneous processing.

This report will illustrate some results that have been obtained with the central California seismic array, and will describe briefly the present state of development of the computer-based earthquake detection system. In both of these areas we feel that the developmental goals have been substantially achieved.

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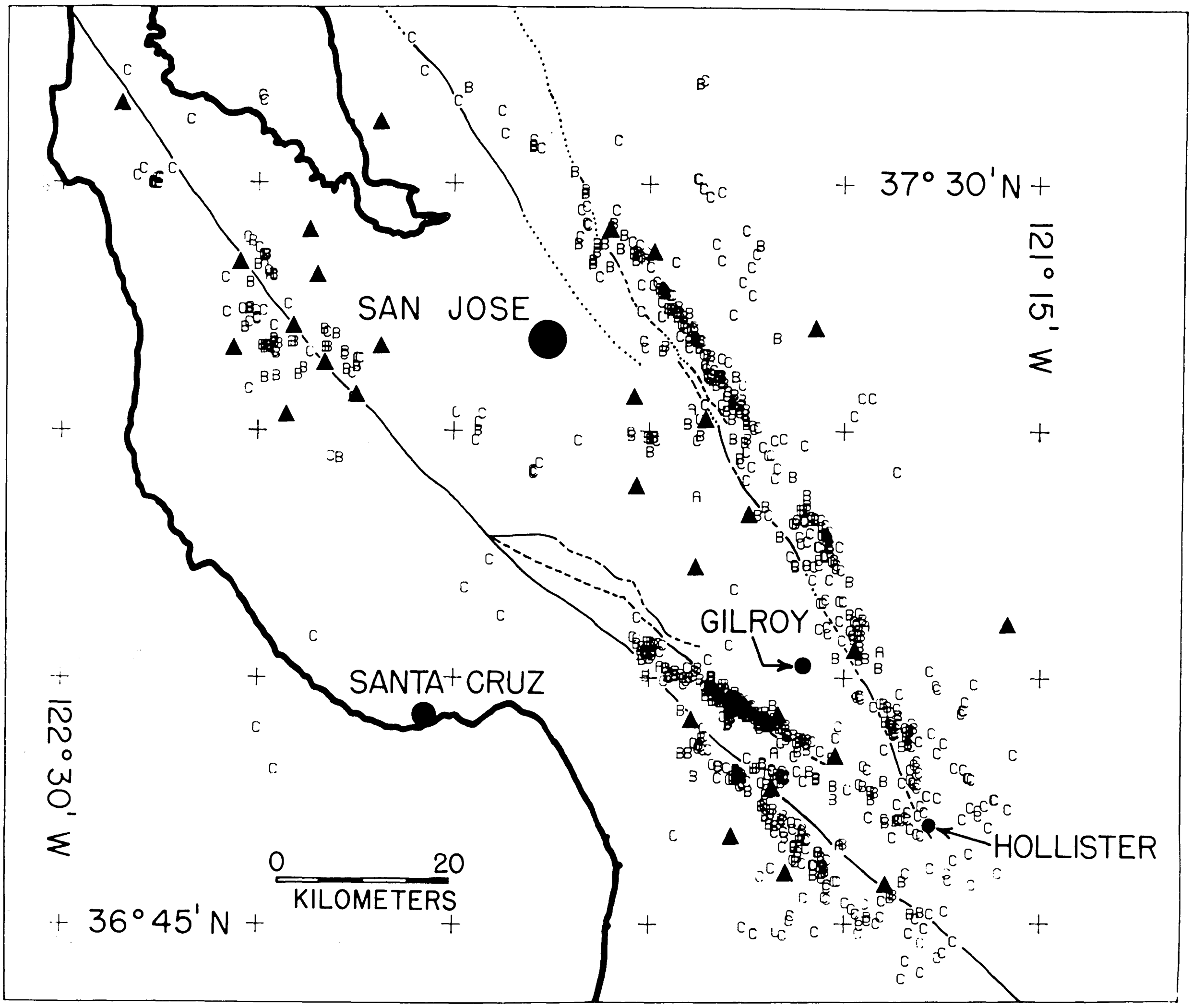

Fig. 1.—Epicentres of earthquakes occurring within the central portion of the central California Coast Ranges seismic array between March 1968 and April 1969. Triangles denote locations of seismograph stations. Letters "A", "B", and "C" indicate the epicentral location and the reliability of the hypocentral determination (see text).

and that progress in this particular approach to the study of active tectonic systems is now under way. Discussion of the computer-based detection system is presented here for the first time.

Central California Seismic Array

Epicentres for approximately 1,000 seismic events occurring in the central portion of the central California seismic network during the period March 1968 through April 1969 are shown in Figure 1. In this figure the epicentres are plotted as a letter "A", "B", or "C". These letters assign to each epicentre a measure of the reliability of its location. Such a rating system is necessary because of the non-uniformity of station distribution within the array. The rating system considers both the statistical parameters calculated in the hypocentre location programme, and certain geometrical parameters. The former group includes the mean deviation of the residuals and the size of the estimated errors in the focal parameters. The latter group includes the number of stations that contributed to the final hypocentral solution, the epicentral distance to the nearest station, and the maximum gap in the azimuthal coverage provided by those stations entering into the final solution. In this rating system "A" denotes an event with a well-determined epicentre and focal depth, "B" an event with well-determined epicentre but only moderately well-determined focal depth, and "C" a moderately well-determined epicentre but essentially unknown focal depth.

In Figure 1 the San Andreas fault zone is shown as a solid line west of San Jose and extending north-west to south-east. The Hayward and Calaveras faults are shown north and east of San Jose extending south-eastward to Hollister. A conspicuous feature is the "N"-shaped or "Z"-shaped configuration of epicentres extending south-east along the Calaveras fault zone to Hollister, thence north-west along the Sargent fault to a point west of Gilroy, thence south-east again along the San Andreas fault zone. The Gilroy–Hollister region, located at the junction of the San Andreas fault with the Calaveras fault, has long been recognised as an area in which micro-earthquakes occur in relatively large numbers. Figure 1 shows that the Sargent fault must play an important role in the tectonic processes currently active in this particular region.

The hypocentres in the Z-shaped zone of Figure 1 tend to define four linear groups. These groups are located (1) slightly east of the Calaveras fault

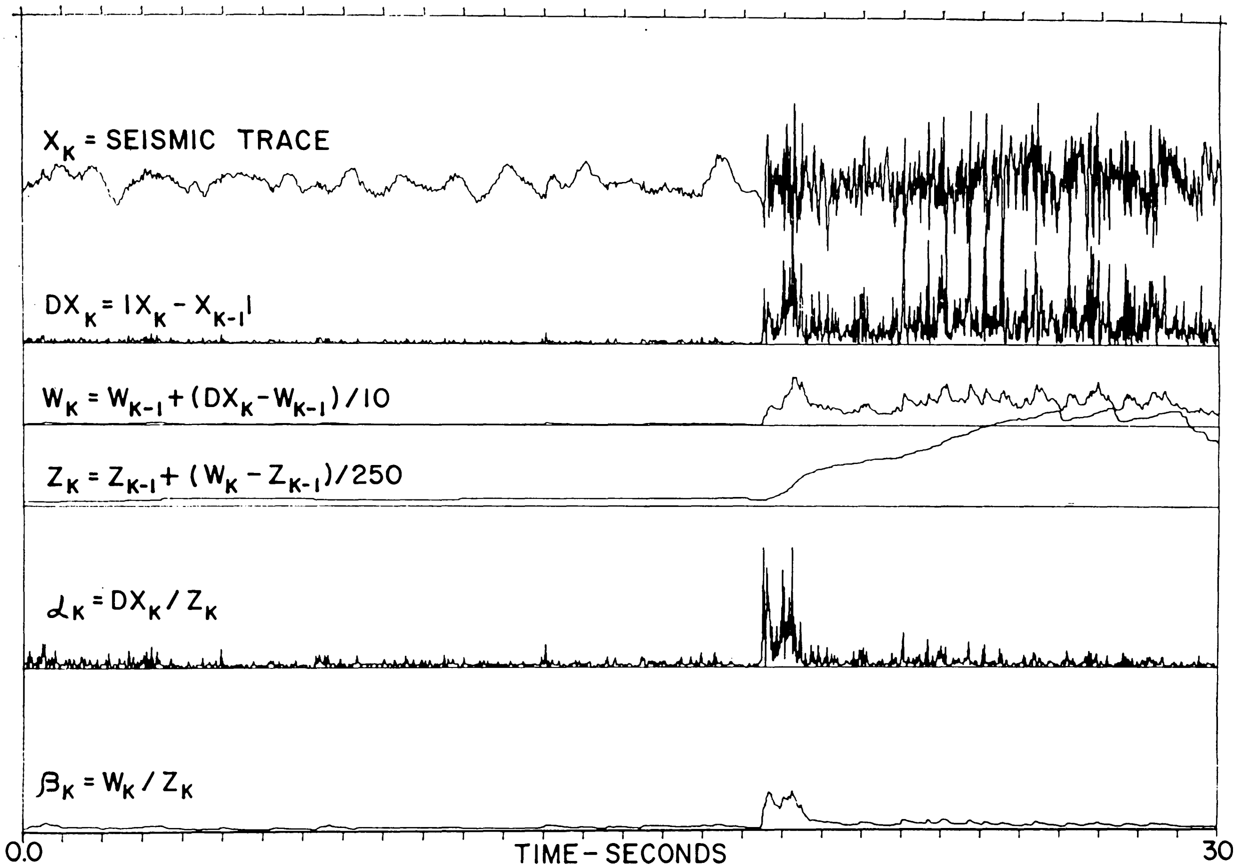

Fig. 2.—The seismic trace (X_k) is an example of a seismic event superposed on a background of relatively high amplitude and low frequency noise. The time variation of the parameters calculated in the real-time detection process is shown in the lower five traces. Both α_k and β_k rise above preset threshold levels (dashed lines), providing confirmation of the onset of seismic energy.

east of San Jose, (2) slightly east of the Calaveras fault east of Gilroy, (3) on the Sargent fault northwest of Hollister, and (4) near the San Andreas fault west of Hollister. For each of these four groups a least-squares plane was fitted to the class A and B hypocentres in two separate calculations. After the first calculation, events lying more than two standard deviations from the plane were discarded, and the calculation repeated with the remaining data. Following the second calculation the standard deviations of the distances from the fitted planes were all less than 1km. The hypocentres analysed in this way define planes of steep dip. For the four linear sections described above the dips are 85°NE, 89°NE, 85°NE and 83°SW respectively. None of the earthquakes has foci deeper than 15km, and most are shallower than 10km.

The systematic alignment of microearthquakes parallel to, but not on, the mapped expressions of the fault traces is another striking feature of Figure 1. The configuration of seismic stations in the region, the relatively good knowledge of crustal velocity structure, and the geologic mapping available would seem to substantiate the offset of the epicentres from the mapped fault traces. It seems preferable, however, to reserve judgment until further studies are completed. It should be noted that the epicentre map of Bolt and others (1968) shows a similar offset for epicentres near the San Andreas fault west and south of Hollister.

Real-time Detection of Microearthquakes

This section describes a particular method of processing earthquake data that has been implemented on an experimental basis. The method is intended mainly for real-time processing applications, although it is adaptable to off-line processing as well. The method is designed to pick only the onsets of relatively impulsive events that occur within a dense seismic array, and to discriminate against teleseisms, unwanted transient signals, and large secondary phases.

The design of an algorithm for automatic detection of local seismic events has been guided by a few simple considerations. First, the algorithm must not be so complex, nor must it require so much analysis of past data, that the computer is unable to keep up with the incoming flow of new seismic data. For local seismic events in California each seismic trace is sampled at an interval of 0.010 seconds for input into the computer. This means that only 10 milliseconds are available for all computer processing until the next sample is ready for conversion and processing. If one intends to monitor 32 seismic channels at a time, then the time available for processing each data point is reduced to approximately 310 microseconds.

Second, automatic detection based upon waveform correlation from one station to another will not work for local seismic events. This is because the signatures written by a local event at stations only a few kilometres apart are remarkably dissimilar.

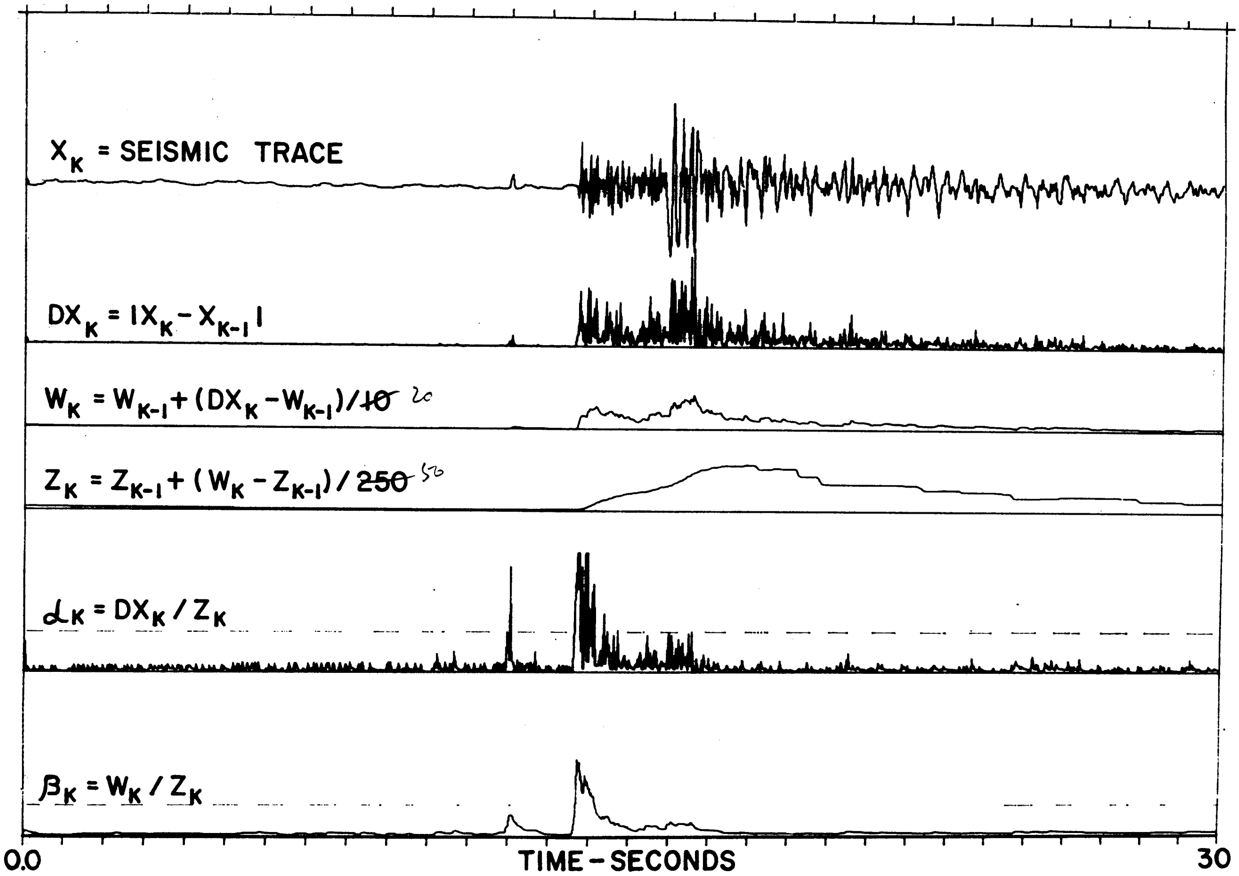

FIG. 3.—The seismic trace (X_k) is an example of a seismic event preceded by a nonseismic transient. The time variation of the parameters calculated in the real-time detection process is shown in the lower five traces. Both α_k and β_k rise nearly simultaneously above present threshold levels (dashed lines) only for the seismic event, thereby eliminating the transient event as a possible seismic onset.

Moreover, the processing time for correlation methods would become excessive. This has led us in the direction of examining separately each incoming seismic channel for the possible onset of a local event.

Further considerations have to do mainly with the realities of real-time recording. That is, microseismic noise levels will vary from station to station and from time to time, unwanted transients having frequency components within the range of local events will appear, and stations will go " out " for varying lengths of time.

Figures 2 and 3 illustrate the method of calculation and detection presently used in the computer algorithm. X_k represents the seismic trace input to the computer where $_k$ is the current time epoch. (In these figures the " tic " marks are one second apart, and the seismic trace has been digitised at a rate of 50 samples per second.) DX_k is the " conditioned " seismic trace, in this case X_k differenced and rectified. Differencing of adjacent data points has the effect of filtering out low frequency components, generally resulting in an improved signal-to-noise ratio for high-frequency microearthquake signals. This is seen most clearly in Figure 2. W_k is a recursive approximation to a 10-point moving average of DX_k. It may be regarded as a " short-window " average that reflects the transient behaviour of DX_k. Z_k is a recursive approximation to a 250-point moving average of W_k. In Figures 2 and 3 Z_k is amplified by a factor of five, with respect to X_k, DX_k, and W_k, so that its behaviour may be seen more clearly. The purpose of Z_k is to give a slowly varying estimate of the amplitude of DX_k, in order to calculate the dimensionless parameters α_k and β_k described below. Although Z_k has the desirable property that, at the onset of an earthquake, it increases more slowly than W_k, it would also have the undesirable property that it decreases more slowly than W_k during the coda phase of the earthquake. This is undesirable because a relatively large Z_k renders the detection process relatively insensitive to the onset of a second impulsive event within the coda of the first.

To reduce this possibility, Z_k is compared to W_k at every time epoch $_k$. If Z_k exceeds W_k then Z_k is reduced by the amount $(Z_k—W_k)/4$. The behaviour of Z_k in the coda phase is illustrated in Figure 3.

The parameters α_k and β_k are used to test for the onset of an earthquake. The dashed-horizontal line associated with these parameters represents a predetermined threshold limit. α_k is a dimensionless quantity (i.e., independent of the amplitude of the incoming seismic signal) that measures the instantaneous amplitude DX_k as compared to the average trace amplitude Z_k. It has the desirable property that, within a few seconds of the onset of an earthquake, it decreases in amplitude, tending to prevent large secondary phases from exceeding the threshold value. β_k is a dimensionless quantity that represents the short-time average of the conditioned trace DX_k with respect to the long-time average.

The parameters DX_k, W_k, Z_k and α_k are calculated at every sampling epoch $_k$, for every seismic trace being monitored. When the current value of α_k exceeds its threshold value, then that time epoch $_k$ is taken as the onset time of what may be an earthquake. Confirmation of an earthquake on that particular seismic channel is sought by calculating the parameter β_k. If β_k exceeds its pre-assigned threshold within, say, one second after α_k was set, then that event is identified as an earthquake on that particular channel. If, after one second, the β-threshold is not exceeded, then the tentative indication obtained by α_k is disregarded, and calculation and checking of α_k resumes. This is illustrated in Figure 3, where a nonseismic transient precedes a clear seismic event by approximately two seconds. In this case the nonseismic event exceeds its α-threshold but not its β-threshold, thereby being excluded as a seismic event.

In addition to the trace-by-trace processing and decision-making described above, simple properties of the arrival-time pattern within the seismic array itself can be used to decide if the event should be regarded as an earthquake. Two criteria have been implemented here. The first requires that the event be identified on some minimal number of seismic stations. In the usual case of an array of 12 or more stations, an event recorded at less than four stations is automatically eliminated by the computer. This has the effect of sorting out very local events whether of seismic or nonseismic origin. A second criterion requires that a β-confirmation of an event at one station be followed within some interval of time by a β-confirmation of an event at another station. If this is not the case, then the confirmation at the earlier station is disregarded, and processing continues as if a confirmation had not occurred. This has the effect of eliminating transients that occur at relatively large time intervals, such as sonic booms.

At the present time the computer continuously scans up to 32 incoming seismic-data channels. P-phase onset times and maximum amplitudes are output automatically to a teletypewriter within one-half minute of the occurrence of an earthquake within the central California seismic array. The one-half minute lag is to allow sufficient time for propagation of the wave train to all stations within the network; it is not a function of the execution speed of the detection programme itself. Although onset times and maximum amplitudes are sufficient to determine hypocentral locations and magnitudes, such calculations are not made during the real-time process described here.

The computer programme utilises about 2,500 words of core storage for execution, and requires about 260 microseconds to process one digital data point for each seismic channel. Thus, if seismic channels are sampled at intervals of 0.01 seconds, the system is capable of processing as many as 38 channels at a time.

A sampling of comparisons between hand-picked and computer-picked onset times indicates that the agreement is very good. In the majority of cases the agreement is better than ± 0.1 second. Minor changes in the computer programme to increase the quality and reliability of the computer-picked onset time are in progress.

Summary

The use of dense clusters of short-period seismic telemetry stations is revealing the details of microseisimicity patterns along a portion of the San Andreas fault system in central California. Epicentres appear to outline the mapped traces of the major faults in the region, but are systematically displaced a few km away from the surface expressions of the faults. Well-located hypocentres define planes dipping at angles greater than 80°. Nearly all the earthquakes are at depths between near-surface and 10km, and none have been calculated deeper than 15km.

Real-time automatic detection and processing of microearthquakes occurring within a relatively dense seismic telemetry array is being carried out on an experimental basis. A computer system connected directly to the central California seismic telemetry lines processes up to 32 channels of data. The system outputs to a teletypewriter the onset times and amplitudes of microearthquakes occurring within the seismic array. The system has applications both to real-time monitoring of seismic and other parameters relating to active deformational processes, and to off-line processing of large amounts of microearthquake data generated by dense seismic arrays.

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