5. Historical Earthquake Re-analysis Project

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5.1 Introduction

The objective of this USGS NEHRP funded two-year project, that commenced in March, 2000, is to characterize the spatial and temporal evolution of the San Francisco Bay Region (SFBR) seismicity during the initial part of the earthquake cycle as the region emerges from the stress shadow of the great 1906 San Francisco earthquake. The problem is that the existing BSL seismicity catalog for the SFBR, which spans most of the past century (1910-present), is inherently inhomogeneous because the location and magnitude determination methodologies have changed, as seismic instrumentation and computational capabilities have improved over time. As a result, the SFBR seismicity since 1906 is poorly understood.

Creation of a SFBR catalog of seismicity that is homogeneous, that spans as many years as possible, and that includes formal estimates of the parameters and their uncertainty is a fundamental prerequisite for probabilistic studies of the SFBR seismicity. The existence of the invaluable BSL seismological archive, containing the original seismograms as well as the original reading/analysis sheets, coupled with the recently acquired BSL capability to scan and digitize historical seismograms at high resolution allows the application of modern analytical algorithms towards the problem of determining the source parameters of the historical SFBR earthquakes.

Our approach is to systematically re-analyze the data acquired from the archive to develop a homogeneous SFBR catalog of earthquake location, local magnitude (M_L), moment magnitude (M_w), and seismic moment tensor (mechanism), including formal uncertainties on all parameters which extends as far back in time as the instrumental records allow and which is complete above appropriate threshold magnitudes. We anticipate being able to compile a new SFBR catalog of location and M_L which spans 1927 to the present and is complete at the $M_L \sim 3$ threshold, and of M_w which spans 1911 to the present and which is complete at the $M_w \sim 4.5$ threshold.

In addition to the above analysis, we will also search for sequences of repeating earthquakes. Identification of repeating earthquakes, which are nearly identical in all source properties, provides an internal consistency check on the location and magnitude homogeneity in the catalog over time.

5.2 Background and Motivation

Although the 1910 to present BSL catalog of earthquakes for the SFBR appears to be a simple list of events, one must remember that it really is a very complex data set. It is easy to misinterpret observed variations in seismicity if we do not understand the limitations of this catalog. The existing 1910 to present BSL catalog of earthquakes for the SFBR is inhomogeneous in that it suffers from the three types of man-made seismicity changes identified by *Habermann*, 1987, namely detection changes, reporting changes, and magnitude shifts. The largest change in the detection capability of the BSL seismic station network occurred circa 1927-1931 with the installation of the Wood-Anderson and Benioff seismometers at four seismic stations (BRK, MHC, PAC, and SFB as shown in Figure 15.12) in the SFBR and the resulting increase in sensitivity lowered the threshold for detection of SFBR earthquakes by about 2 M_L units. The most significant reporting change occurred circa 1942 when the BSL began determining M_L for some earthquakes and by 1948 M_L was routinely determined and reported for all SFBR earthquakes listed in the BSL Bulletin (*Romney and Meeker*, 1949). A magnitude shift occurred in 1954 when the response of the Wood-Anderson seismographs changed (owing to changing the free period from 1.0 to 0.8 seconds) (*Bolt and Miller*, 1975).

The lack of a homogeneous catalog of earthquake for the SFBR which spans most of the past century, the availability of the invaluable BSL seismological archive, the interest in the Working Group on California Earthquake Probabilities (WGCEP, 1999), the funding of an initial effort with support from the USGS-PG&E CRADA, and the purchase and loan of a high-resolution wide-format digitizer by the USGS, combine to provide both an incentive and an unique opportunity to systematically re-process, using modern algorithms, the BSL seismographic records and data for SFBR earthquakes and to produce a homogeneous catalog of earthquakes for the region.

5.3 Initial Effort

During the summer of 1998, the USGS funded two students, via a USGS-PG&E CRADA, to transcribe the data from the original BSL reading/analysis sheets to computer readable form. With this funding, they were able to transcribe the reading/analysis sheets for SFBR earthquakes, working back in time from 1983 through 1944 (1984 onward was already in a computer database). The newly transcribed data along with the data already in the database were used to determine systematically the location, M_L, and corresponding uncertainties of earthquakes which have occurred in the SFBR. An interim catalog of SFBR earthquakes was subsequently developed which includes hypocenter, M_L, and their uncertainties, and which spans from 1951 through 1998. The catalog starts in 1951 because amplitude data, used in the determination of M_L, were not registered on the reading/analysis sheets prior to that time. The interim catalog events are plotted in Figure 15.12 and available at `http://www.seismo.berkeley.edu/seismo/herp/`).

The rate of SFBR seismicity (see Figure 15.13) inferred from the 1951-1998 Interim Catalog is: log N = 4.105 - 0.890 M_L. Assuming that the annual rate of SFBR seismicity ($M_L \geq 3$) is stationary, we expect to observe an average of 27 earthquakes per year.

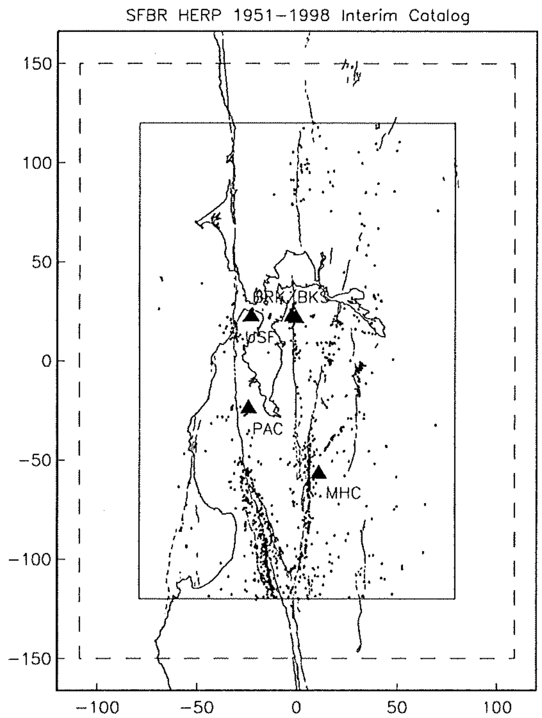

Figure 15.12: Map of the San Francisco Bay Region showing the Interim 1951-1998 Seismicity and the Stations which have housed Wood-Anderson seismographs. The solid inner box defines the SFBR (as given in the WG-CEP 99 Report) and the dashed box is a 30 km buffer zone in which candidate SFBR events are also analyzed.

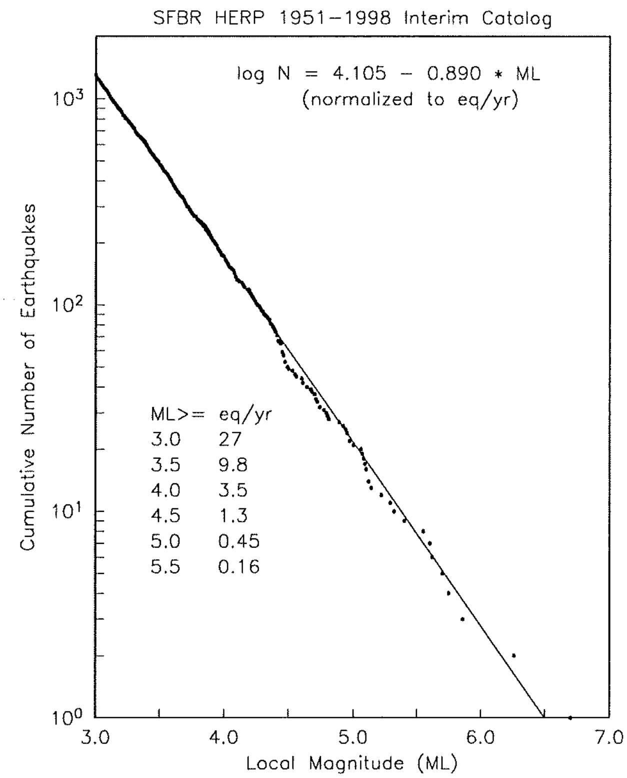

Figure 15.13: SFBR rate of seismicity inferred from the 1951-1998 catalog.

5.4 Progress During the First Year

Since the Wood-Anderson maximum trace amplitude data used in the determination of M_L were not registered on the original reading/analysis sheets kept in the BSL archive, we read the maximum trace amplitudes recorded by the Wood-Anderson seismograms in order to calculate M_L and its uncertainty. The manpower intensive task of reading the maximum trace amplitudes registered by the Wood-Anderson seismograms for Berkeley (BRK), Mt. Hamilton (Lick Observatory; MHC), Palo Alto (Banner Station; PAC), and San Francisco (USF) that are kept on store in the BSL seismogram archive in Edwards Stadium was completed by June 2001. We began with the 1950 records and worked backward in time and finished reading the earliest Wood-Anderson records (circa 1927) in June 2001.

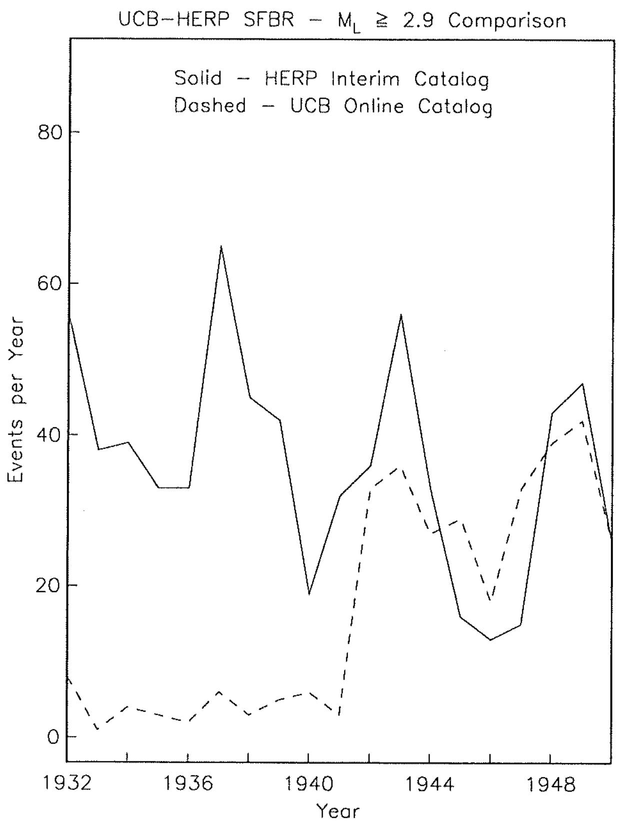

Figure 15.14: Number of 1932-1951 SFBR events analyzed (solid line) compared to the number of events listed in the BSL on-line catalog. Note that prior to 1942, the BSL on-line catalog does not list a large number of the events occurring in the SFBR owing to the fact that, since they had only a descriptive location rather than geographical coordinate location listed in the Bulletin, they were not transcribed when the computer readable database was initially compiled in the mid-1960's.

A list of candidate SFBR events, which included all events in the UCB catalog of earthquakes and also all events in the BSL Bulletins that were within the SFBR (including the 30 km buffer zone) and which either had a M_L of 2.8 or larger or else no M_L assigned, was compiled. The UCB catalog for the pre-1951 era is a composite based on the analysis of instrumental recordings and felt reports (*Bolt and Miller*, 1975). As we progressed back in time prior to 1951, the proportion of events with no M_L assigned increases and prior to 1942 it is virtually 100 percent. The number of 1932-1951 events analyzed is shown in Figure 15.14. To expedite the processing, we read the microfilm copies of the MHC Wood-Anderson seismograms (*Uhrhammer*, 1983) to cull out events which are below the M_L 2.8 threshold and thus minimized the number of records that we had to deal with in the BSL seismogram archive.

Originally, we did all the seismogram reading in the seismogram archive in Edwards Track Stadium and the students spent a significant amount of time shuttling between the BSL facilities in McCone Hall and Edwards Track Stadium. To expedite the processing, we transferred the seismogram bundles for the years that were being read to McCone Hall and this proved to be much more efficient.

5.5 Progress During the Past Year

We discovered a significant number of instances where the phases and maximum trace amplitudes were easily readable on the Wood-Anderson seismograms but there were no corresponding phase entries on the original reading/analysis sheets. Consequently we had to read the phase onset times for a numerous events that occurred prior to 1951. This process was quite tedious and time consuming owing primarily to the necessity of determining the clock corrections that convert the time on the record to Universal Time (UT). Clock corrections relative to a radio time standard were tabulated daily and linearly interpolated to determine the clock correction for a given event. The time corrections were occasionally unreliable (particularly so at USF) so we had to use relative times (the time difference between the P-wave and S-wave onsets) in place of absolute times when using the data to locate an event. The photographic paper was occasionally placed on the recording drums emulsion side down which resulted in faint and unreadable traces. Seismograms were occasionally fogged (inadvertently exposed to light) which also rendered them generally unreadable. Some seismograms are also difficult or impossible to read owing to the trace being out of focus due to misaligned optics.

We have finished transcribing the 1910-1927 data (pre-Wood-Anderson instrument) data. Prior to the advent of the Wood-Anderson seismographs, there were only two seismic stations operating in the Berkeley network, namely at the Student Observatory on the Berkeley Campus (BRK) and at the Lick Observatory at Mt. Hamilton (MHC). It should be noted that the earliest stations were operated at astronomical observatories primarily because these observatories had the means to routinely determine accurate clock corrections required for interpretation of data recorded on the seismograms. During the pre-1927 era, the primary seismic instrumentation at BKS and MHC consisted of Bosch-Omori and Wiechert seismographs which operated at low magnification (100x) and recorded on smoked paper.

We are also scanning and digitizing selected pre-1934 events recorded by Weichert and Bosch-Omori seismographs and the corresponding Wood-Anderson seismograms for those cases where the event was also recorded by Wood-Anderson seismographs. The primary objectives are to calibrate the determination of magnitude from the pre-Wood-Anderson recorded events and to begin the process of acquiring digital representations of the pre-1932 smoked paper seismograms. Obtaining digital representations of the Bosch-Omori and Weichert smoked paper seismograms is crucial particularly because the earliest smoked paper records, kept on store in the Berkeley Seismogram Archive, are becoming quite brittle and difficult to handle. We have been scanning these seismograms mostly on a flat bed scanner because some of the records could be damaged if they are passed through the rollers in the large format scanner.

5.6 Fuzzy-Logic-Based Location Algorithm

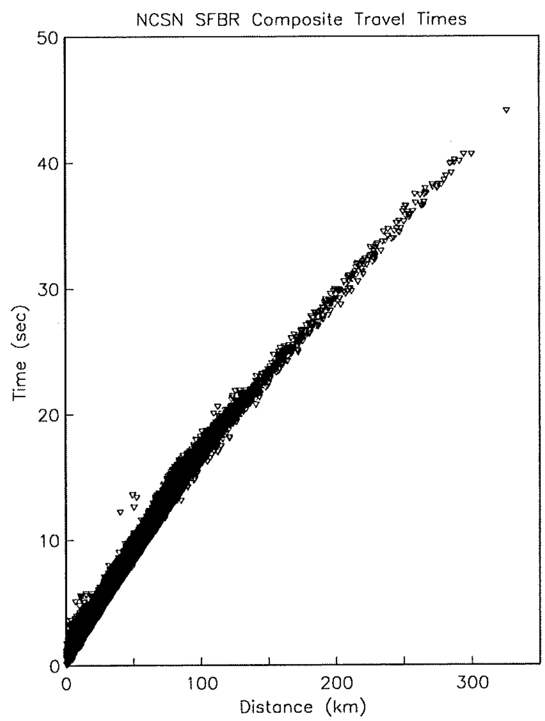

Figure 15.15: Observed travel times from SFBR earthquakes to NCSN SFBR stations. Plotted are travel time data from 1984-2000 for which the original waveforms are available on the NCEDC.

The end goal of HERP is to develop a uniform and internally consistent catalog of SFBR seismicity for instrumentally recorded earthquakes which have occurred during the past century in the region. As a part of this goal, we need to develop and calibrate a procedure for obtaining robust earthquake locations throughout a time when the number of SFBR seismic stations evolved from the initial two stations (BRK and MHC) at the turn of the last century to the more than 100 seismic stations at present. The complex geology and faulting observed in the SFBR results in seismic wave propagation times which scatter significantly over differing propagation paths in the region as shown in Figure 15.15. Initially, the events are being located using a one-dimensional velocity model with appropriate station adjustments. Ultimately, however, a three-dimensional velocity model will be preferable for locating SFBR earthquakes.

We found that the existing earthquake location algorithms do not provide robust solutions when using the potentially imprecise data available from the sparse four-station pre-1960 SFBR seismic network. The distribution of observed P-wave travel times for the SFBR is shown in Figure 15.15. Consequently, a fuzzy logic based algorithm was developed to facilitate the determination of robust earthquake locations (*Uhrhammer*, 2001). The algorithm inherently has a high tolerance for imprecision in the observed data and it can yield robust sparse network solutions without requiring that the problematic observed data be either identified, down-weighted, or removed. This characteristic also renders the algorithm ideally suited for use in automated systems, such as the REDI Project, which provide rapid earthquake information.

5.7 Acknowledgements

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5.8 References

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