San Francisco Bay Region Historical Earthquake Re−analysis Project

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Robert Uhrhammer

Berkeley Seismological Laboratory, 207 McCone Hall #4760
University of California, Berkeley, CA 94720−4760
Telephone: 1.510.642.8504
Fax: 1.510.643.5811
E−mail: bob@seismo.berkeley.edu

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INVESTIGATIONS UNDERTAKEN:

Introduction

The objective 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 region emerges from the stress shadow of the great 1906 San Francisco earthquake. The problem is that the existing Berkeley Seismological Laboratory (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.

Creation of a SFBR catalog of seismicity that is homogeneous, that spans as many years as possible, and that includes formal estimates of the uncertainty in the estimated parameters is a fundamental prerequisite for probabilistic studies of 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 BSL computational capabilities allows the application of modern analytical algorithms towards the problem of determining the source parameters, including formal uncertainties, 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 (Mw), 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. In addition to the above analysis, we are also searching 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.

Background

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 one does 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 Wood−Anderson seismometers at four SFBR stations (BRK, MHC, PAC, and USF) and the resulting increase in sensitivity lowered the threshold for detection by about 1.5 M_L units. The most significant reporting changes occurred circa 1941−1942 when the BSL Bulletin entries changed from descriptive to geographical coordinate locations and the reporting of local magnitude began. A magnitude shift occurred in 1954 when the response of the Wood−Anderson seismographs was 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 earthquakes 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−analyze, using modern algorithms, the BSL seismographic records and data for SFBR earthquakes and to produce a homogeneous catalog of earthquakes for the region.

Initial Effort

During the summer of 1998, the USGS, via the USGS/PG&E CRADA, funded two students 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 for SFBR earthquakes, working back in time from 1983 to 1944 (1983 onward was already in computer database). The 1951−1998 data were used to systematically determine the location and local magnitude (including their formal uncertainties) of earthquakes which have occurred in the SFBR and an interim catalog of these events has been compiled and is available via URL: http://perry.geo.berkeley.edu/seismo/herp/. The interim catalog starts in 1951 because the maximum trace amplitudes, used in the determination of M_L, were not registered on the reading/analysis sheets prior to that time.

Current Effort

Our current effort has concentrated on the processes involved with expanding the database of SFBR earthquakes. This involves: compiling a list of candidate SFBR events using a combination of the UCB online catalog and the events listings in the BSL Bulletins; reading the maximum trace amplitudes recorded on the Wood−Anderson seismograms (~1932 forward) and on the Bosch−Omori and Wiechert seismograms (pre−1932), and; transcription of the amplitude data and the reading/analysis sheet data. When this process is complete, we will have a computer readable database of SFBR earthquake phase and amplitude data, complete at appropriate magnitude thresholds (M_L ~3 from ~1930 and M_L ~4.5 pre ~1930), which spans approximately the past 90 years.

Concurrent with the transcription and seismogram reading effort, we are compiling a list of candidate events (M_L ~4.5 and larger) for scanning and digitizing the relevant seismograms for moment tensor analysis. We have thus far concentrated on processing the pre−1964 SFBR events because there are plans underway to digitize the broadband seismic records that are stored on analog magnetic tapes in lieu of scanning and digitizing the paper seismograms. The primary incentive for digitizing the analog tape recordings is that the resulting resolution is a factor of eight higher than the resolution which can be obtained from scanning and digitizing the paper records. The BSL analog magnetic tape archive contains short−period recordings from 8−11 BSL SFBR seismic stations (varied over time) and broadband recordings from three SFBR seismic stations. The tape digitization effort will likely start this summer.

Also concurrent with the above efforts, we are beginning the search for candidate repeating SFBR earthquakes. We expect to find repeating earthquakes in the SFBR with recurrence intervals of order 10 to 50 years and since the new catalog will span 70+ years at the M_L ~3 threshold, we could potentially identify repeating sequences of up to 5 events. Once a sequence of repeating earthquakes is identified, there are a couple of intriguing possibilities. Once older earthquakes have been identified as members of a repeating sequence, we can get a much better estimate of their size and location by assuming that they are very nearly the same as their most recent sequence members. This offers a powerful and robust method for constraining the hypocenter location and magnitude of the older earthquake when constructing the SFBR earthquake catalog and it also provides a means of checking the spatial and magnitude homogeneity of the catalog.

ACCOMPLISHMENTS:

The reading of maximum trace amplitudes, registered on the Wood−Anderson seismograms for the 1938−1950 SFBR candidate events, and subsequent transcription to the database is complete. This is a very labor intensive and time consuming task because it involves retrieving, reading, and re−archiving of the original seismograms for four SFBR stations (BRK, MHC, PAC, and USF shown in Figure 1) which are kept in the BSL archive. While reading the Wood−Anderson seismograms, particularly for sequences of events which occurred circa 1942 through1945, we identified several SFBR candidate events (mostly the smaller members of earthquake sequences) for which there was no data in either the Bulletin or in the reading/analysis sheets. These events were subsequently read and added to the database.

A list of SFBR candidate events for 1932−1941 has been compiled from the information in the BSL Bulletins. This task was complicated by the fact that there was rarely any local magnitude information available and that, prior to July 1941, the locations were descriptive (with geographical coordinates rarely provided) and the event times were only accurate to within a couple of minutes [Byerly and Meeker, 1948]. Consequently, most of the SFBR candidate events, that occurred prior to July 1941, are not in the UCB online catalog (available from the Northern California Earthquake Data Center via URL: http://quake.geo.berkeley.edu/ncedc/catalog−search.html). An algorithm was subsequently developed to convert the descriptive locations to geographical coordinates and P−wave and S−wave onset times (registered in the Bulletin) at generally the closest station were used to estimate the origin time to within a few seconds. The resulting list contained 721 candidate SFBR events (see Figure 1) while the UCB online catalog derived list contained only 270 events for the same area and time span. We are in the midst of reading the Wood−Anderson seismograms and transcribing the data for the 1932−1941 SFBR candidate events. At our present rate of progress, this task ought to be completed in approximately 6 weeks.

Analyzing the 1910−1927 data has proven quite a challenge. There are only two stations reported in the BSL Bulletin (BRK and MHC) prior to 1927 and the available event information from the UCB online catalog is rather sparse with the origin time only accurate to a within a couple of minutes and the location typically given only in terms of distances from the stations and/or where the event was reported felt. To resolve ambiguity in the location when using data from only two stations, we resort to felt reports and comments from the original reading/analysis sheets and also, when the need arises, to the extensive newspaper archive in the UCB main library. Determination of the magnitude of these events is based on amplitudes registered on the Bosch−Omori and Wiechert seismographs (generally reported in microns on the reading/analysis sheets). We have identified 360 candidate SFBR events which occurred between 1910 and 1931 and we are systematically analyzing these events, working back in time. This task ought to be completed within 4 months.

In order to compile a list of candidate repeating earthquakes we have developed an algorithm to search for all sets of earthquakes which have nearly identical observed S−

P time intervals observed at the SFBR stations, which have similar magnitudes, and which form a roughly periodic sequence in time. This candidate list greatly reduces the number of events which need to be examined to identify sequences of repeating earthquakes. The Wood−Anderson seismograms play a crucial role in this analysis since they recorded SFBR earthquakes over a time span of more than six decades.

As noted above, the pre−1960 SFBR events were generally recorded by the four stations (BRK, MHC, PAC and SFB; shown in Figure 1) located in the region and the phase data (typically P− and S−wave onset times) recorded on the reading/analysis sheets have a generally unknown level of accuracy owing to the presence of occasional clock errors, reading errors, and/or transcription errors (station SFB was particularly troublesome with frequent clock errors so only the S−P time interval was reliable). Also, the pre−1927 SFBR events were only recorded by two stations (BRK and MHC) which presents a challenge in that the resulting location ambiguity needs to be resolved. Location algorithms which employ the minimization of a misfit function do not produce robust solutions when these types of errors or problems are present in a sparse data set. In order to obviate the man−power intensive reading of phase onset times from the original seismograms, a fuzzy logic (Yen and Langari, 1999) based location algorithm (FL_RELP; Fuzzy Logic Regional Earthquake Location Program) for locating the SFBR earthquakes is being developed. The FL_RELP algorithm utilizes and builds upon some of the components that were developed for its predecessor, namely BW_RELP (Broadband Waveform Regional Earthquake Location Program) (Dreger et al., 1997; Uhrhammer et al., in press, 2001). FL_RELP uses a adaptive grid search algorithm to map the possibility function for all observational subsets and also to determine the maximum in the cumulative possibility function. The inconsistent data are essentially inhibited from influencing the solution by using an appropriate threshold for mapping the possibility function. The most powerful argument in favor of the fuzzy logic approach is it ability to obtain a robust solution when using a sparse set of imprecise observed data that may contain inaccuracies and/or errors. Preliminary tests indicate that up to approximately one−third of the data can have large residuals (in the classical least−squares sense) without significantly influencing the solution. This capability along with the fact that the algorithm does not require the determination of which data are inaccurate or erroneous means that the algorithm is also ideally suited for use in automated seismic event location schemes.

An abstract "The San Francisco Bay Region Historical Earthquake Reanalysis Project: A progress report and relocating pre−1960 instrumentally recorded earthquakes using a fuzzy−logic−based algorithm" has been submitted for presentation at the 2001 SSA annual meeting in San Francisco.

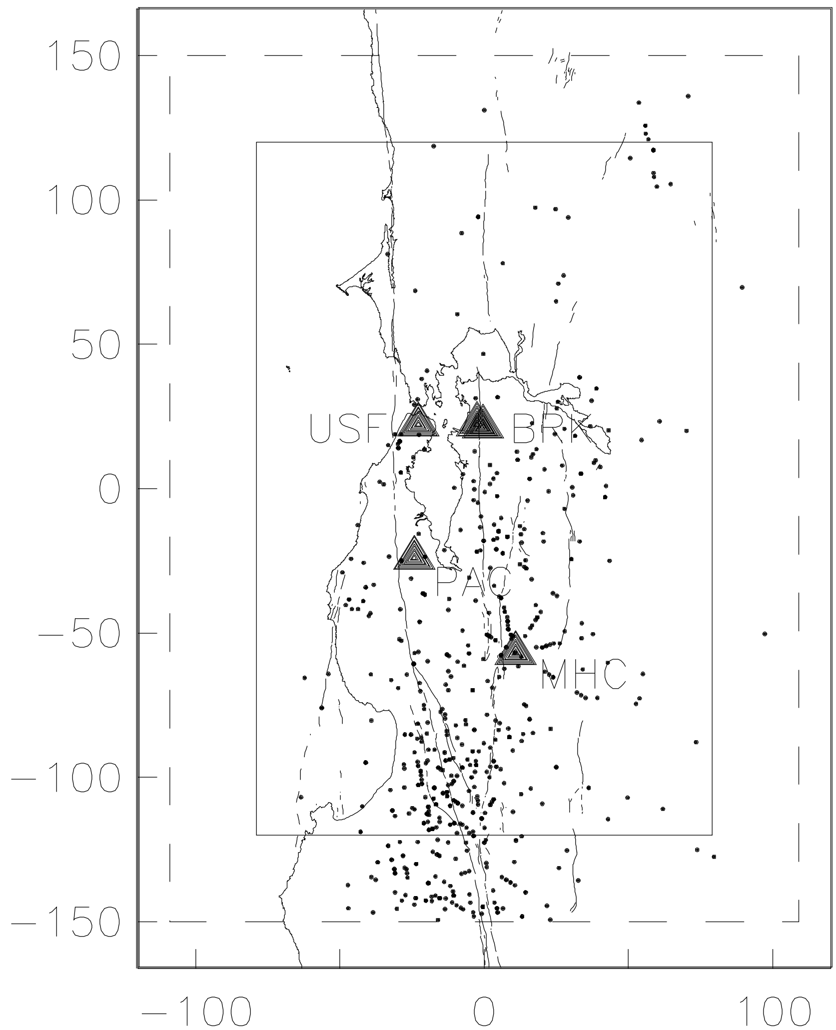

Figure 1. Map of the SFBR study area (inner box) and 30 km buffer zone (dashed box) showing the locations of the stations housing Wood−Anderson seismographs (triangles) and the preliminary locations of the 721 candidate SFBR earthquakes that occurred between 1932 and 1941 (dots). The distances are in km. The "candidate" SFBR events are those events which have an initial location estimate within the SFBR (including a 30 km buffer zone around the SFBR) and which either have no M_L assigned or they have an initial M_L estimate of either 2.8 or larger (1932−present) or 4.3 or larger (pre−1932). In order to minimize the number of seismograms in the BSL archive that need to be analyzed, we have been scanning the microfilm records of the seismograms from the Lick Observatory station to cull events from the SFBR candidate list which are smaller than the appropriate threshold M_L. The microfilming of the 1911 through June 1962 MHC seismograms was done in 1981 as a pilot effort of the Historical Seismogram Filming Project [Uhrhammer, 1983].

UNANTICIPATED PROBLEMS:

While we expected the reading and analysis of the seismograms to be time consuming, we found that it was taking more time than we anticipated owing largely to the fact that the seismogram archive, the reading/analysis sheet archive, and the BSL facilities with the computer work stations and the high−resolution scanner were in different buildings scattered across the Berkeley campus. The students working on the project had to spend time at three separate sites to do the work and this proved to be a somewhat inefficient use of their time. To expedite the processing, we adopted a modern factory model and reorganized one room in McCone Hall (the main BSL facility) for doing all the required reading, transcription, and analysis. We now transport the seismograms and the reading/analysis sheets to McCone Hall as they are needed and re−archive them when the processing is done (in annual batches). This change has successfully increased our overall productivity in reading, transcribing, and analyzing the SFBR earthquakes.

NON−TECHNICAL SUMMARY:

This project focuses on the creation of a seismicity catalog for San Francisco Bay Region earthquakes that is homogeneous, that spans as many years as permitted by the instrumental records kept on store in the Berkeley Seismological Laboratory archives and that includes formal estimates of the uncertainty in the estimated parameters. Such a catalog is a fundamental prerequisite for probabilistic studies of the regions seismicity and for characterizing the spatial and temporal evolution of the seismicity during the initial part of the earthquake cycle as the region emerges from the stress shadow of the great 1906 San Francisco earthquake.

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The interim 1951−1998 SFBR seismicity catalog is accessible online (see the data availability section below).

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Data Availability

The interim 1951−1998 catalog of seismicity for the SFBR is available online via URL: http://perry.geo.berkeley.edu/seismo/herp/. This web page is currently being revised. For further information, contact Robert Uhrhammer by e−mail (bob@seismo.berkeley.edu) or by telephone at 1.510.642.8504.