Theme IV – Understanding Seismicity Catalogs and their Problems

What is an instrumental seismicity catalog?

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Contents

Abstract

Seismicity catalogs are one of the basic products that an agency running a seismic network provides, and is the starting point for most studies related to seismicity. A seismicity catalog is a parametric description of earthquakes with each entry describing one earthquake; for example each earthquake has a location, origin time, and magnitude, and may have additional metadata such as associated uncertainties and focal mechanism information. At first glance, this seems to be an easy data set to understand and use. In reality, each seismicity catalog is the product of complex procedures that start with the configuration of the seismic network, the selection of sensors and software to process data, and the selection of a location procedure and a magnitude scale. The human-selected computational tools and defined processing steps, combined with the spatial and temporal heterogeneity of the seismic network and the seismicity, makes seismicity catalogs a highly heterogeneous and complex data set with as many natural as human induced obstacles. This article is intended to provide essential background on how instrumental seismicity catalogs are generated and focuses on providing insights on the high value as well as the limitations of such data sets.

1 Motivation

Seismicity catalogs are one of the most important products of seismology. They provide a comprehensive database used for studies related to seismicity, seismo-tectonics, earthquake physics, and seismic hazard analysis. The scientific and technological advances in recent decades have enabled seismologists to produce various types of earthquake catalogs, which provide essential parameters to describe an earthquake; however, in most cases these parameters are not uniformly determined because the underlying basic information available to determine the parameter values are substantially different.

1.1 History

The development towards seismometers in today's sense started in the middle of the 19th century; a milestone was the first recording of an earthquake in Japan [Rebeur-Paschwitz, 1889] with a seismometer in Potsdam, Germany (a short historical overview is given at: http://earthquake.usgs.gov/learn/topics/seismology/history/history˙seis.php).
In the 19th and early 20th centuries earthquake parameters were in general inferred from intensity measurements that describe the effects and damage distribution caused by an earthquake, up until the mid 1930s in much of the world, sometimes supplemented by instrumental recordings. A prominent example for such a data set is the archive of yearly reports on effects of earthquakes observed in and around the Swiss national territory since 1878, including intensities smaller than three at the Swiss Seismological Service [Fäh et al., 2003]. Some areas were instrumented with sparse networks as seismometers were developed. For example, 7 instruments were installed and recording earthquakes in California starting in the 1920s, with an increase in the number of stations usually following large earthquakes. A detailed description of the network development for Southern California is provided by Hutton et al. [2010]. Starting in the early 1970s, developments in electronic and mechanical engineering as well as telecommunication made it possible to deploy hundreds of seismometers and remotely retrieve data via telemetry. Seismometers with a limited frequency bandwidth were installed globally and the recorded ground motions were transmitted following a conversion from analog to digital data. Starting in the 1980s, broadband seismometers were invented and installed, now often co-located with Global Position System (GPS) receivers for precise timing and location.

Obviously, seismic networks were installed according to the needs of society and research; often changes occurred following large earthquakes. Similarly, earthquake catalogs evolved over time increasing the information content. Global and regional networks have different focuses, which are also reflected in their earthquake catalogs.

In the following, we differentiate between **pre-historic, historic and instrumental seismicity catalogs**:

1) Pre-historic catalogs are based on trenching data or subsidence records collected by earthquake geologists. For instance, earthquake geologists have established a ~2000 year long earthquake record for the San Andreas fault.
2) Historical catalogs comprise data from the assessment of an intensity field, from the analysis of waveforms from early instruments, usually recorded on paper that in some cases are scanned and digitized. These cover the period from the first human descriptions up until (but not limited to) the onset of instrumental catalogs. A good example of such a data set can be accessed at the Archive of Historical Earthquake Data (AHEAD) at http://www.emidius.eu/AHEAD/.
3) Instrumental seismicity catalogs are defined as data that is produced from a dense seismic network with automated data transfer and processing delivering a location and magnitude for seismicity starting in the 1970s or later. The Southern California Data Center serves as a good example: http://www.data.scec.org/gen˙info.html

The evolution of earthquake catalogs varies around the globe; two relevant examples are descriptions of the Swiss earthquake catalog [Fäh et al., 2003; Nanjo et al., 2010] and the description of southern California earthquake catalog [Hutton et al., 2010]. Spatial and temporal differences in available data cause differences in the accuracy, precision and expected uncertainty for hypocenters listed in a catalog. All three types of catalogs are essential to address different questions in seismology with the pre-historical and the historical seismicity catalogs playing a major role in assessing long-term seismic hazard, instrumental catalogs as resource for a multitude of applications in statistical seismology.

Historical and instrumental catalogs share parameters and parameter values, but there are differences in how these parameters are determined. As an example, the hypocenter for an earthquake in an instrumental catalog is computed from the arrival times of seismic phases picked from waveforms recorded at seismic stations. The inversion or grid search is done using available software modules [e.g. Lee and Lahr, 1975; Lienert, 1994; Lomax et al., 2000; Klein, 2002]. The magnitude is often determined from the maximum amplitude in the waveform or from the coda duration.
In contrast, the hypocenter of an earthquake in historical times is inferred from regression analysis of the observed intensity field [Bakun and Wentworth, 1997; 1999; Musson, 1998; Gasperini et al., 1999]. Similarly, the magnitude is inferred from a regression of instrumental magnitudes and the size of areas of a selected intensity value.

1.2 Objectives

The objective of this article is to highlight the value of instrumental seismicity catalogs – valuable information that is a result of a complex process of automated processing and human decision. At the same time we outline the limitations of the parameters and parameter values provided in a catalogue. Thus, this article provides an overview of the challenges and tasks a seismologist or seismic network operator faces when generating an instrumental seismicity catalog – issues of historical earthquake catalogs are discussed in Gasperini et al. [CORSSA, Theme IV].

This article introduces the details of the procedures used to determine the catalog and identifies the technical and scientific challenges: a catalog can never be understood without knowing the procedures it was derived from. The objectives are to

1) provide awareness about the accuracy of parameter values in a catalog,

2) provide the catalog user with background knowledge / tools to assess the quality of the catalog,
3) introduce the background of the procedures used to determine the catalog parameters and their values,
4) introduce an overall understanding of the range of uncertainties.

1.3 Prerequisites and benefits for the reader

To make best use of this article, the reader should be familiar with basic terminology used in seismology. It is also desirable that the user have initial understanding of how the catalog parameters describe an earthquake and maybe an earthquake catalog at hand for which an analysis shall be done.

After reading the article, the reader will understand the background of how an instrumental earthquake catalog is created and will be able to work out and understand the strengths and limits of the catalog for her analysis.

2 Seismological Practice

An entry in an instrumental seismicity catalog that describes best estimates for the location, origin time, and magnitude of a single earthquake is created following a detailed procedure that is different for each seismic network. This procedure maybe an expression of the specific requirements a network operator has to fulfill, the specific network instrumentation and network geometry, and the computer software used for processing. Here, we describe the general process, and network specifics should be available from each network operator.

2.1 Seismometer – Seismic Network

Seismologists analyze waveforms detected by a **seismometer** and recorded by a datalogger at a seismic station. A number of seismic stations that are analyzed together form a **seismic network**. In modern practice, the data from all of the stations of a seismic network are transmitted by radio, internet or satellite in real-time to a central site, the data center, where the data are processed and the earthquake catalog is produced.

Different types of seismometers exist that are sensitive to different signals, and hence are used in different circumstances. Short-period seismometers are used by local seismic networks to record the relatively high-frequency seismic signals of close-by micro-earthquakes (magnitude ¡ 3). These stations are usually placed close together, with average station spacing on the order of a few 10s of km, to capture these small earthquakes. Long-period seismometers are used in global catalogs to record the relatively low frequency signals of larger earthquakes recorded at greater distances, usually over the entire globe. Strong motion seismometers are designed to record the very large ground motions produced in the near field of a major earthquake, and are often used in engineering applications. Broadband seismometers are capable of recording both high frequency and long period signals, and often have high dynamic range, so that they can record micro-earthquakes through major earthquakes on scale.

Seismometers detect ground motions at their location that are constantly generated through the unrest of the earth called seismic noise. **Seismic noise** is caused by multiple sources such as wind, human activity, and ocean waves. The noise characteristics of a seismic station, or seismic network, along with the station geometry, influence which earthquakes can be detected, the quality of the recordings, and hence the quality of the catalog.

2.2 Ground motions and seismic waves – Important phases

Ground motions excited by seismic waves set the stage for locating an earthquake. Seismic waves are excited during the rupture process of an earthquake; distinct seismic waves are generated and created during the rupture process but also while travelling through the Earth (see e.g. Lay and Wallace [1995]).

The seismic phases that can be identified on a seismogram depend on the source-station distance. Local networks, which typically record earthquakes at distances of d ¡ 100 km, usually only pick the direct arrival of the body waves. The direct P-wave is most often the first arrival at these distances. The direct S-wave is often more difficult to identify, especially on vertical single-component records, because of interference from the P-wave coda. Therefore, local earthquake phase catalogs contain many more P-waves than S-waves.

At regional distances (>100 km), picking body-waves becomes more difficult, because the source-station distance can exceed the cross-over distance where the first arrival is not the direct P-wave, but a P-wave that has been refracted along the Moho. This cross-over distance depends on the seismic velocity and the depth of the Moho. To use these phases in a location code, a 1D layered velocity model with an appropriate Moho depth is needed.

Global networks, which monitor large earthquakes recorded world-wide at teleseismic distances, identify more phases, benefiting from the dispersion of the seismic wave-train and additional reflected and refracted phases. In particular, surface waves (Love and Rayleigh waves; see Aki and Richards, [2002]; Lay and Wallace [1995]) are important at teleseismic distances because their amplitude decays more slowly than the amplitudes of body waves. Another important class of phases are depth phases: phases that are reflected off density/velocity discontinuities in the earths structure; these phases are often used to improve the accuracy of the focal depth and to decrease uncertainties in the depth determination. The delay of phases which initially reflect from the free surface, relative to the more direct phase, also helps constrain the earthquake depth.

Picking and identifying phases can be complicated by the ambiguity of phases (e.g. picking the S-wave out of the P-wave coda), and if the signal to noise level is low. The exact onset time of a phase can also be ambiguous if it rises slowly out of the noise. The picks of such phases are referred to as “emergent”, and are generally considered less accurate than “impulsive” phases that rise quickly above the noise level; categorizing the errors during the picking procedure is not standardized and thus mainly qualitative and subjective (CORSSA article by Husen and Hardebeck, 2010). As a consequence, not all networks provide quality factors although this is essentially needed to quantify the location accuracy and uncertainty. The Southern California Seismic Network and the Swiss Seismological Service, for example, assign a quality factor of E or I for “emergent” or “impulsive”. In addition, they assign weights to each phase from 0 to 4, with 0 being best, and 4 being so bad that the pick should not be trusted. The weight is an estimate of the time uncertainty of the pick.

Usually, a computer code calculates continuously the short and long-term averages from the waveforms, and determines the onset of a phase from a sudden change in the waveform. The associator code continuously tries to associate all available phases into an earthquake. If 4 or more phases associate, the associator declares an event and passes those phases to the next processing step, which will determine the hypocenter. Requiring the minimum number of four/five picks originates from basic **inverse theory** constraints that are used to determine the hypocenter. The more picks are available, the better the hypocenter determination, but four or more phases detected at different stations are necessary to resolve the origin time (t) and location $\mathbf{x}$=(x,y,z).
Once phases have been detected and picked on individual seismograms, the phases for a single earthquake recorded at the different stations need to be associated together. The association of a phase with an event is straight-forward for an isolated event, but

becomes more difficult during times when many events are occurring. A prominent example is the occurrence of a large earthquake that is followed by an aftershock sequence: in the first seconds to hours, signals of aftershocks are often hidden in the Coda of the mainshock. Thus, the software to identify phases automatically misses the onset of new events. In general analysts and researchers have to use sophisticated tools, such as their own eyes, to analyze these complex signals [Peng et al., 2006].

Common practice is for an automated system to first make the phase picks and associations, which are later reviewed and revised by an analyst during post-processing.

As an example, a phase data file from the Southern California Seismic Network retrieved using the software STP (http://www.data.scec.org/STP/stp.html) is given below. The output for each event begins with a line containing event location information. Each subsequent line lists the phase picks for one channel with the following fields: network, station, channel, two-digit location code, latitude, longitude, elevation, phase, first motion (dilatational or compressional), signal onset quality ("i" for impulsive, "w" for weak), pick weight, epicentral distance, and time after origin time:

```
10167485 le 2006/02/01,06:39:26.210 36.0207 -117.7710 1.91 0.95 l 1.0
CI WCS EHZ -- 36.0270 -117.7676 1135.0 P d. i 1.0 0.77 0.337
CI WCS EHZ -- 36.0270 -117.7676 1135.0 P d. w 1.0 0.77 0.370
CI JRC2 HHZ -- 35.9825 -117.8089 1469.0 P c. i 1.0 5.44 1.072
[...]
```

2.3 Earthquake location

Earthquake location, although a primary task of seismologists, is a field of active research for multiple reasons. The earthquake location problem is a classic non-linear inverse problem that is in most instances is solved as a linearized problem [Lee and Lahr, 1974; Lienert, 1984]. In recent years, non-linear location methods such as proposed by Lomax et al. [2000] have become increasingly available and implemented, however these are not yet standard tools that are used for routine earthquake location by seismic networks.

To locate an earthquake, it is necessary to have a velocity model of the earth, for P- and S-waves. The velocity model is usually obtained from the same type of P and S wave arrival time information that is used for locating earthquakes. Because of the inherent coupling of the earthquake locations and seismic velocity model, the accuracy of the earthquake locations will depend on the accuracy of the seismic velocity model. Most seismic network locations are computed based on a 1D-velocity velocity model, 3D-velocity models are rarely used in seismic network operation. Depending on the true lateral velocity variations, there may be systematic shifts of earthquake hypocenters compared to their true location. The accuracy of the earthquake location process can be calibrated using events for which the true hypocenter parameters are known, such as mine blasts and quarry blasts.

Seismic networks take steps to minimize the effect of unmodeled 3D velocity structure on earthquake locations. Some networks, for example the Northern California Seismic Network [Oppenheimer et al., 1993], account for large-scale lateral variations in velocity structure by dividing the network area into regions with different 1D seismic velocity models. Much of the velocity heterogeneity is often near the surface, and can be accounted for through an individual station correction at each receiver. Because all rays arriving at a station travel approximately vertically through the near-surface below the station, a static time offset applied to all arrivals is often an adequate correction for near-surface structure.

The basic data that are determined by the seismic network and used in earthquake locations are the arrival times of various seismic phases. The accuracy of the arrival times depends on how accurately the waveforms are timed. Modern network instruments typically obtain the time from GPS receivers, and hence the timing is usually quite accurate. The previous generation of short-period analog networks, often time stamped all the data at the central recording site, thus providing excellent relative time. However, for some older recordings, and for deployments without GPS timing or with older types of timing receivers, there may be substantial time offsets that must be identified and corrected before arrival time information can be used to locate earthquakes. In some cases, where S-P times can be used to locate earthquakes, absolute timing is not needed.

More details on the general earthquake location problem, including uncertainty and accuracy, will be found in the CORSSA article by Husen, S., and J.L. Hardebeck (2010),

2.4 Earthquake magnitude issues

There are numerous different magnitude scales (see e.g Lay and Wallace [1995]), based on different kinds of measurements. Choices about which magnitude scales to use vary across different seismic networks. Often a single network will use different magnitude scales for different sized events or report multiple types of magnitudes for a single event. Although attempts are made to calibrate the different magnitude scales so that they are similar within the relevant magnitude ranges, there can be considerable variation between different magnitude estimates for a single event. This heterogeneity may produce artifacts in the statistical distribution of magnitudes in a network catalog.

The most commonly used class of magnitude scales, following from Richter□s original local magnitude scale, is based on the logarithm of the amplitude of the recorded seismic waves. Local magnitude, denoted M_L, is arbitrarily defined based on the maximum observed amplitude on a Wood-Anderson seismometer, with a period of 0.8 sec, recorded at 100 km from the earthquake (Richter, 1935; Hutton et al. 2010). In practice, of course, the recording distance is not exactly 100 km, and corrections must be made to account for amplitude changes with distance due to attenuation and geometrical spreading. Station corrections are usually determined, to account for site conditions. Corrections must also be made for recordings on instruments other than the now-obsolete Wood-Anderson. Local magnitudes are best suited to small local earthquakes with predominately high-frequency energy.

Other scales have been developed that are based on the log of the amplitude of a particular phase, the most common being two scales for teleseismic (global) recordings: the body wave magnitude, m_b, based on body waves with periods of several seconds (Gutenberg and Richter, 1956), and the surface wave magnitude, M_S, based on 20 second surface waves (Gutenberg and Richter, 1956). These magnitude scales are used for most globally-recorded earthquakes, but are not appropriate for the largest earthquakes, those of magnitude greater than 7 or 8. This is because the energy at high frequencies saturates for large events, e.g. the 1 second energy radiated by a magnitude 8 earthquake is similar to the 1 second energy radiated by a magnitude 7 earthquake. The body wave and surface wave magnitudes therefore saturate at around magnitude 7 to 8. Therefore, some of the largest earthquakes in a catalog may be of much higher magnitude than reported.

The moment magnitude, M_W, scale (Hanks and Kanamori, 1979) is based on the log of the moment of the earthquake, rather than on the amplitude of a particular phase at a particular frequency, and therefore has the advantage that it does not saturate for large magnitudes. The seismic moment of an earthquake is usually estimated by fitting a double couple moment tensor solution to the recorded waveforms from the earthquake. Alternatively, for well-recorded earthquakes, the moment can be estimated from a finite source model of the earthquake.

For all magnitude scales, it is clearly important to calibrate the gain of the recording instruments, and calibrate the attenuation model used to reconcile observations at different distances. The calibration parameters are often coupled together, and coupled to the earthquake magnitudes, presenting a formidable inversion problem. For an example of the difficulty in calibrating magnitude scales, Tormann et al. (2010) document the substantial effects of the recalibration of magnitude scales in California, which was done to achieve consistent magnitude estimates across the state.

One type of magnitude that is independent of amplitude is the coda duration magnitude, M_D, which is based solely on the duration of the seismic signal [Eaton, 1992]. Coda duration magnitude is intended for locally-recorded events, where the various reflected and refracted phases are not well separated and instead form a prolonged coda following the initial phase arrivals. The amplitude of the coda diminishes as the reflected and refracted phases attenuate, and the larger the initial waves, the longer the duration of the observable coda. Although this magnitude scale requires no amplitude calibration, it does require empirical calibration of event durations, as well as corrections for distance, and event depth. One potential artifact is that coda duration magnitudes may be biased towards larger magnitudes during aftershocks sequences or other times of intense seismicity, as additional earthquakes may occur within the coda of the first event and lengthen it.

3. Parameters provided in an instrumental seismicity catalog

Resulting from the above-described procedures, an instrumental seismicity catalog is a list of earthquakes that consist of the basic parameters and other optional desired parameters. The **basic parameters** include:

1) An event identification number or a tag formed with letters and numbers that is unique (but often not sequential). A unique identifier (ID) of an entry in a seismicity catalog is needed to keep track of changes to parameter values in the seismicity catalog.
2) The location (hypocenter) of an earthquake in a reference system (latitude / longitude / depth)
3) The origin time of an earthquake (date, time with at least 0.01 sec precision)
4) Magnitude or multiple magnitudes for the earthquake

Optional parameters that are essential for some uses of the catalog, but often not provided, describe further properties that are inferred from the seismic waveforms or otherwise associated with an earthquake:

1) Uncertainty bounds on magnitudes:
   Depending on the magnitude type, a component magnitude is calculated for each seismometer component at a station. The earthquake magnitude is then either defined as the mean or the median of the component magnitudes (other definitions may exist). The uncertainties are often given as one standard deviation or mean average deviation (MAD) assuming an underlying Normal distribution of magnitudes. This is a strong assumption that may not always hold.
2) Uncertainty limits on location parameters, horizontal and vertical (e.g. Bondar et al., 2004; Gomberg et al., 1991).
   It is also important to know which program was used for locating the earthquakes in the catalog since the uncertainty definitions differ. For example, Hypo71 [Lee and Lahr, 1974] provides one standard deviation bounds, Hypoellipse [Lienert et al., 1984], and Hypoinverse [Klein, 2002] provide error ellipses and NonLinLoc [Lomax et al., 2000] provides a full probability density description of the errors.
   The uncertainty gives insight in the precision of the location, but not the overall accuracy. The accuracy depends on the velocity model, which is rarely provided with the catalog, thus the uncertainty limits are likely to be too small compared to the real, but unknown error.
   The horizontal and vertical uncertainties depend strongly on the network geometry; vertical and horizontal uncertainties also depend differently on number of phases N_{Obs}, the minimum distance to the closest station (DISTMIN), the

Greatest Azimuthal GAP (GAP), the secondary GAP

3) Number of observations to determine location (N_{Obs})
The number of phases (P and S) that are used to locate an earthquake hypocenter, as well as the distances to the closest stations recording P and S.
4) Greatest Azimuthal Gap, or the largest angle where there are no stations:
5) Secondary GAP:
Second greatest azimuthal gap between stations used in the location
6) Root mean square of the fit: RMS
Root means square of the overall residuals of the modeled compared to the observed travel-times.
7) Minimum Distance to the closest station from the epicenter (DISTMIN)
8) Parameters describing the focal mechanism (strike or dip direction, dip, rake) and their uncertainty
In catalogs that include the focal mechanism, it is usually unknown which of the two nodal planes is preferred. Only source directivity or alignment of aftershocks can help with selecting which of the two nodal planes could be the actual fault plane.
9) Phase picks and pick quality (examples given in section 2.2):
Information on phase picks can include
   - Phase name (P, Pg, PN, PmP, S, …)
   - Signal onset quality: e.g. impulsive, emergent [Diehl et al., 2009]
   - Pick uncertainty bounds
   - True time or time after origin time
10) Type of event:
Differentiation between tectonic event, quarry blast, induced earthquake, and so on; see for example Fäh et al. (2003)
11) Maximum intensity (I_M)
12) Epicentral intensity(I_0)

The parameters listed above denote parameters of an instrumental seismicity catalog. In general, not all parameters are available for all events; this is due to the policies the network operators follow when producing the catalog or when storing data. It is also a function of time and space, dependent on technical developments and human resources.

As a reminder, all catalog are the result of waveforms recorded by a complex, spatially and temporally heterogeneous seismic network, processed by humans using a variety of software and assumptions. Consequently, the resulting catalog is far from being calibrated, in the sense of a laboratory physical experiment. Even the best earthquake catalogs are heterogeneous and inconsistent in space and time because of seismic networks' limitations to detect signals, and are likely to show as many man-made changes in reporting as natural ones [Habermann, 1987; Habermann, 1991; Habermann and Creamer, 1994; Zuniga and Wiemer, 1999].

4. Data Format

There is no community accepted data format for an earthquake catalog the distribution of earthquake data is the responsible of the network operator and depending on the resources different formats are offered, ranging from rather simple ASCII-formats to complex XML-based formats based on an explicit data scheme.

A recent community-based initiative provides one of the most comprehensive data scheme describing an entry an earthquake catalog and is called QuakeML. This can be accessed at https://quake.ethz.ch/quakeml/QuakeML.

Software to further process data often requires reformatting and it is out of the scope of this article to provide an overview.

5. Summary

A seismic network earthquake catalog, while seemingly a simple collection of basic earthquake parameters such as location, magnitude and origin time, is the result of numerous decisions and processing steps, each of which affects the quality of the final catalog. The first step is to choose where to install what kinds of seismometers to collect waveform data. The next step is the detection of signals rising above the noise level, and associating together these signals, sometimes called phase arrivals, recorded at the various stations in the network. Once the phase arrivals are associated together, the earthquakes are located using the phase arrival times and a crustal velocity model. The earthquake locations are highly dependent on the choice of velocity model. Earthquake magnitude is computed from the amplitude and/or duration of the signal, with essential calibrations. As well as the basic earthquake parameters of location and magnitude, many seismic networks also provide additional information that can be used to assess the quality of the locations and magnitudes [e.g. Deichmann et al., 2009]. Many networks also provide the phase data and the original waveform data, for researchers to compute their own catalogs using different techniques or assumptions.

6. Links to online earthquake catalog providers

The following list is an incomprehensive selection with which the authors are familiar and have referenced in this article – many more exist.

The extended list for accessing earthquake data of international, national and regional centers is provided by the The Pacific Northwest Seismic Network provided by S. Malone at http://www.pnsn.org/seismosurfing.html

Links to data providers:

California Integrated Seismic Network (CISN)
http://www.cisn.org/

Earthquake catalog of Switzerland:
http://www.seismo.ethz.ch/prod/catalog/index

European-Mediterranean Seismological Center (EMSC)
http://www.emsc-csem.org/

Global Centroid Moment Tensor Project
http://www.globalcmt.org/

National Earthquake Information Center (NEIC)
http://earthquake.usgs.gov/regional/neic/

Southern California Earthquake Data Center: http://www.data.scec.org/gen˙info.html

Southern California Seismic Network:
www.scsn.org

Historical earthquake data for the Euro-Mediterranean region:
Archive of Historical Earthquake Data (AHEAD)
http://www.emidius.eu/AHEAD/

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