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Seismic monitoring

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INTRODUCTION TO SEISMIC MONITORING

Relevance and Rationale for Monitoring

Although earthquakes happen frequently in many parts of the world, any occurrence of a moderate to large event is sudden and unexpected. Thus, the earthquake process can be interesting and even frightening to people. Most earthquakes are associated with natural, dynamic processes that shape Earth's landscape. The vast majority of earthquakes are caused by sudden slip along faults, resulting in seismic waves that shake the ground, often with sufficient force to damage structures or trigger other events, such as landslides. When significant earthquakes occur anywhere in the world, such as the December 2004 tsunami-generating event in Indonesia that killed more than 200,000 people, or the October 2005 earthquake in Pakistan that killed more than 70,000 people, emergency response and relief efforts come from around the globe, and there is renewed interest in understanding the causes and in mitigating the devastating effects of earthquakes.

Earthquakes can be significant hazards, as evidenced by occasional damaging and deadly events. Individuals, governments, and organizations can respond to the hazard by understanding the probability and the likely effects of significant events; preparing emergency response plans; enhancing public knowledge about what to do in case of an earthquake; and taking specific steps (such as reinforcing critical or weak structures) to reduce the risk of earthquakes.

Earthquakes and Seismic Monitoring

Earthquakes are often defined as ground vibrations related to a release of elastic energy, or as the sudden slip of a section of a fault plane, releasing stored elastic energy; the latter is the most common source of significant ground vibrations. The release of **elastic energy** associated with earthquakes generates seismic waves that propagate through the Earth and along the Earth's surface across large distances. Most earthquakes are the result of plate tectonic processes. The Earth's plates are moving at speeds of centimeters per year, which produces deformation at plate boundaries. Due to friction on fault surfaces, faults that make up the plate boundaries generally do not slip continuously. As the plates move, rocks are progressively deformed (strained) along the plate boundaries (often over many years or decades), thus storing elastic energy. When the resulting stress on a segment of a fault plane increases beyond a critical threshold, the fault segment slips, creating an earthquake from the release of stored elastic energy. This process is called **elastic rebound** and was discovered after the 1906 San Francisco earthquake by H.F. Reid (1910) a half century before the development of plate tectonic theory.

The vast majority of earthquakes occur along plate boundaries (Fig. 1) as explained above; this process is best explained by the theory of **plate tectonics** (Kearey and Vine, 1996). Some earthquakes occur in plate boundary or intraplate regions associated with other dynamic geologic processes such as volcanic and hydrothermal activity, reactivation of ancient faults, or **crustal loading** (e.g., topographic loads on the crust such as mountain ranges, water loading due to filling of a reservoir). Some earthquakes are caused by human activity related to filling of reservoirs, detonation of explosions, or injection of fluids into the ground. The dynamic geologic processes that result in earthquakes also create topographic relief and interesting and beautiful landscapes. Many national parks are located in geologically interesting areas that include earthquakes or previous plate tectonic activity.

Many visitors to our national parks are interested in how the features within the park came to be. Thus, the geologic and seismic attractions of the park present an opportunity for public involvement, education, and outreach. Geologic and earthquake displays, brochures, and other information can be used to effectively communicate interesting and important facts and concepts to park visitors. A computer monitor displaying local or relevant earthquake activity and one or more educational seismographs increase interest and enhance the effectiveness of the education

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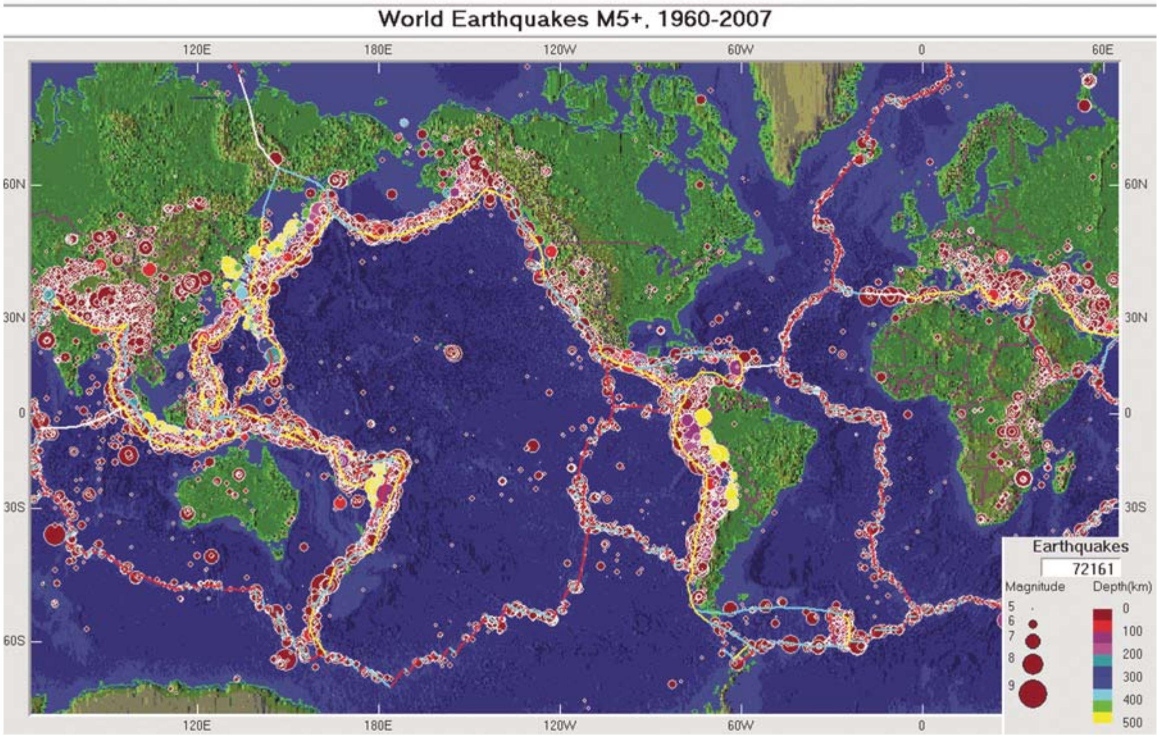

Figure 1. Worldwide earthquakes (M5+, 1960–2007) and plate boundaries (red [divergent boundaries], blue [transform boundaries], and yellow [convergent boundaries] lines; map generated using Alan Jones' Seismic/Eruption program, http://bingweb.binghamton.edu/~ajones/).

and outreach effort. If there is sufficient interest or need because of significant hazard, a more extensive seismic monitoring effort involving a local network of research-quality seismographs may be justified.

Moderate to large earthquakes that are relatively close to an observer may be sensed by the shaking of the ground caused by seismic waves generated by the earthquake. However, even small or distant events can be monitored using sensitive **seismographs** (instruments that record seismic wave motion) which record ground motion and are time synchronized so that the resulting seismograms can be analyzed systematically. By using seismograms from a few or many monitoring stations, one can determine the origin time and location of the event and estimate its **magnitude (M)**—a measure of energy released by an earthquake.

Today, nearly all moderate and larger earthquakes are recorded by seismographs, and most of the recorded events are located using the times of arrivals of seismic waves at seismograph stations. Much of the routine monitoring using global, regional (Figs. 2 and 3), and local seismograph networks has been automated so that event locations and magnitude determinations are often available and distributed online within minutes of an earthquake. Up-to-the-minute online displays of global and regional earthquake activity can be viewed with the IRIS (Incorporated Research Institutions for Seismology) Seismic Monitor at http://www.iris.edu/seismon/ or at the U.S. Geological Survey (USGS) earthquake site, http://earthquake.usgs.gov. Links to U.S. regional and local seismograph networks and near-real-time displays of seismicity and seismograms can also be found at the USGS earthquake site. Instructions for accessing earthquake information online can be found at: http://web.ics.purdue.edu/~braile/edumod/eqdata/eqdata.htm. The USGS/ANSS (Advanced National Seismic System) Web site (http://earthquake.usgs.gov/research/monitoring/anss/products/) contains links to maps and lists of recent earthquakes, shake map displays of ground motion from selected events, hazard maps, and real-time seismogram displays.

Thousands of earthquakes are recorded and located by seismograph stations every year. Many thousands of additional events occur each year but are too small to be recorded, or to be recorded by a sufficient number of stations to be located. The average number of earthquakes per year worldwide is listed by magnitude in Table 1. A frequency-magnitude plot of these data is also shown in Figure 4. The frequency-magnitude plot, also called a **Gutenberg-Richter diagram** after two famous seismologists, represents a fundamental relationship in seismology in which there are about ten times fewer earthquakes within any given area and in any given time period for each increase of one magnitude unit. This relationship is found to be valid for regional and local seismic source zones as well. A frequency-magnitude plot can be used to estimate recurrence intervals. For example,

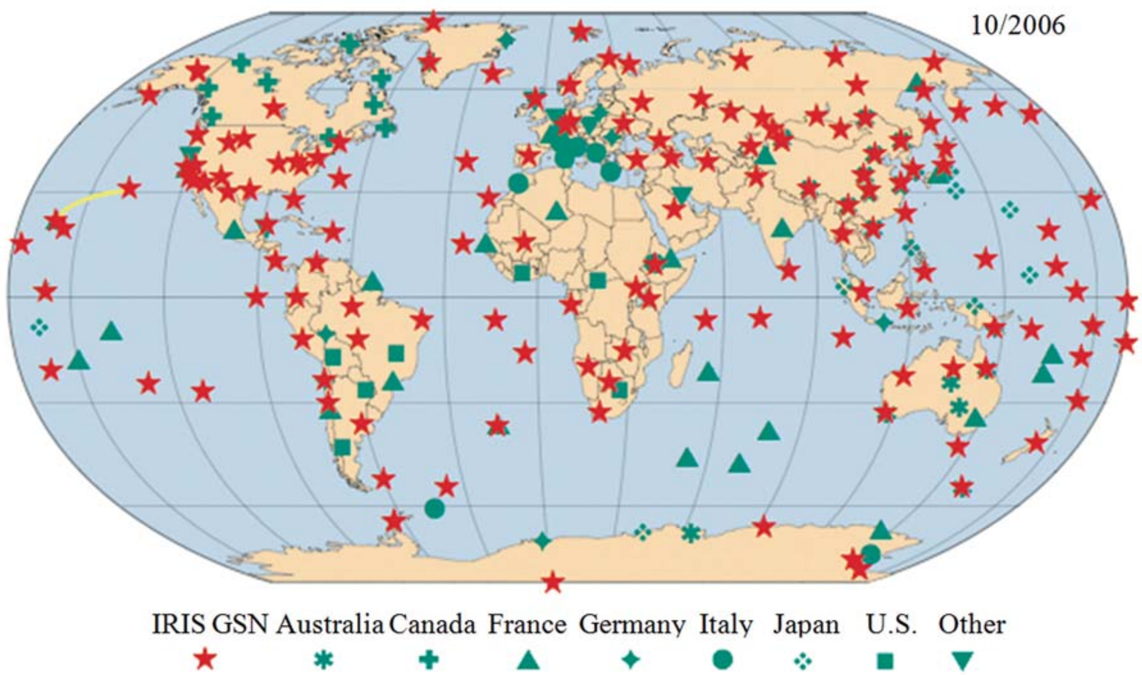

Figure 2. Seismograph stations of the Global Seismograph Network (GSN) and the Federation of Digital Broadband Seismic Networks (FDSN). Map from IRIS, http://www.iris.edu.

from the frequency-magnitude plot shown in Figure 4, we can estimate that there should be ~150 magnitude 6 or greater earthquakes in the world every year, or about one M6+ event every two to three days. A quick look at a list of recent earthquake activity, such as the USGS last 30 days catalog, accessible at http://earthquake.usgs.gov, verifies this estimate. The recurrence interval provides a very useful earthquake forecasting method that can be used for any seismic source area for which sufficient earthquake data are available to allow calculation of a reliable frequency-magnitude plot.

CAUSES OF EARTHQUAKES AND TIME VARIATIONS IN EARTHQUAKE ACTIVITY

As stated previously, the vast majority of earthquakes are caused by plate motions, and ~95% of all earthquakes occur in plate boundary areas. A relatively small number of earthquakes occur in intraplate regions, on reactivated ancient faults, and in areas of crustal loading not directly associated with plate boundaries. Although most earthquakes are related to plate boundaries, some plate boundaries are very wide and diffuse. An example is the complex plate boundary region in western North America in which convergent, divergent, and transform plate boundaries exist in the coastal area and just off the coast. These currently active plate tectonic processes affect the entire western United States. This tectonic activity is evidenced by the widespread seismicity of the western United States (Fig. 5). The seismicity map in Figure 5 also illustrates one of the online tools (the IRIS Event Search) that can perform a catalog search and create a map of earthquake activity for any area in the world.

The time distribution of earthquakes is largely random, though recurrence intervals do provide a probability estimate of the average time between events of a specified magnitude. Because plate motions are continuous, earthquake activity over time is expected to be similar to past activity.

In any given seismic source area, earthquake activity often consists of relatively well-defined "sequences," such as mainshock/aftershocks; foreshock/mainshock/aftershocks; pairs or triplets of significant events; swarms; or long-term, random time distributions that can result in two or more closely spaced significant events, with long periods between such events. Despite some successes and considerable interest and efforts in earthquake prediction, there currently is no consistently reliable method for predicting earthquakes, so significant events occur suddenly and without warning. However, areas of potentially significant earthquake activity are well known, and statistical analysis of past events, including the frequency-magnitude relation, provides valuable estimates of future activity and earthquake hazards.

VITAL SIGNS AND METHODS FOR SEISMIC MONITORING

Seismic monitoring utilizes sensitive seismographs to record the ground motion from seismic waves created by earthquakes or

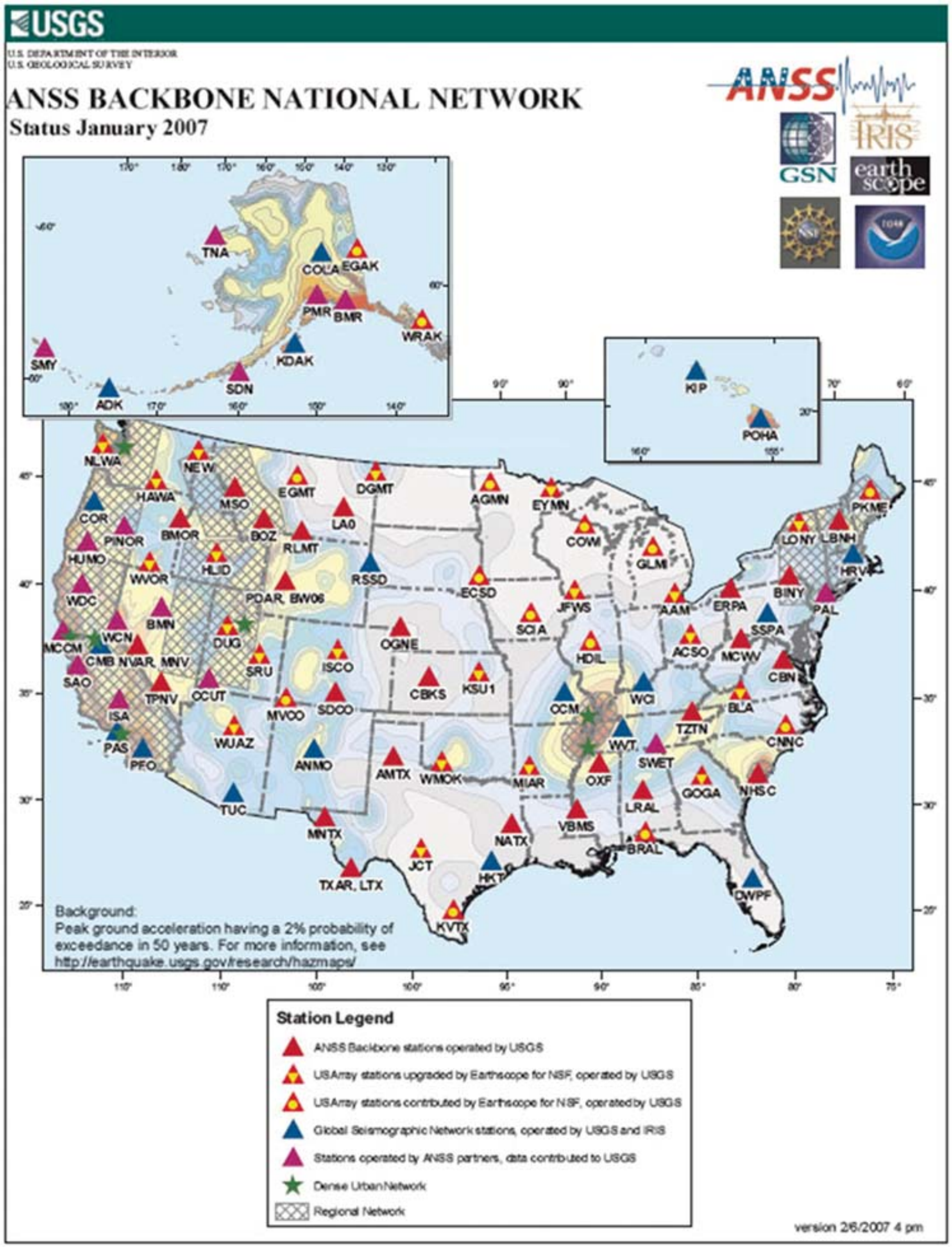

Figure 3. Seismograph stations of the U.S. Advanced National Seismograph System (ANSS). Map from the U.S. Geological Survey, http://earthquake.usgs.gov/research/monitoring/anss/.

other sources. Seismograms from seismic monitoring stations can be used to determine the location, origin time, and magnitude (as well as other characteristics) of earthquakes. The detection ability of a seismograph or network of seismographs is dependent upon the type of instruments, the availability of accurate timing, the number and locations of stations relative to the earthquake location, the size of the earthquake, and the ambient ground vibration noise level.

An excellent description of seismic monitoring is contained in the U.S. Geological Survey Circular 1188 (1999), available at http://pubs.usgs.gov/circ/1999/c1188/circular.pdf. Circular 1188 describes the basic concepts of seismic monitoring (section 2), outlines plans for a modern national seismograph network, the Advanced National Seismic System (ANSS), and describes the major benefits and uses of seismic monitoring. These benefits and uses include: earthquake emergency management, warnings of volcanic eruptions, warnings of earthquake-generated tsunamis, seismic hazard assessment, earthquake engineering, seismology research, public information, and education. Seismic monitoring is also described in *Earthquake Monitoring: Then and Now*, available at http://earthquake.usgs.gov/learning/eqmonitoring/eq-mon-6.php, and in Ansell and Taber (1996), Stein and Wysession (2003), and Bolt (2004). Further information on seismology, earthquakes and earthquake hazards can be found in Abbott (2006), Bolt (1993, 2004), Bolt et al. (1977), Bryant (1992), Hough (2002), Keller and Blodgett (2006), Kovach

TABLE 1. GLOBAL FREQUENCY OF EARTHQUAKES BY MAGNITUDE

Descriptor	Magnitude	Average annually
Great	8 and higher	1*
Major	7–7.9	17†
Strong	6–6.9	134†
Moderate	5–5.9	1319†
Light	4–4.9	13,000 (est.)
Minor	3–3.9	130,000 (est.)
Very minor	2–2.9	1,300,000 (est.)

Note: From U.S. Geological Survey (http://neic.usgs.gov/neis/eqlists/eqstats.html).
*Based on observations since 1900.
†Based on observations since 1990.

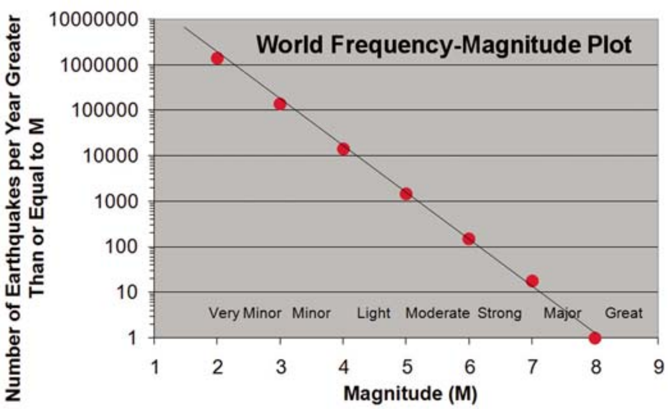

Figure 4. World frequency-magnitude plot (data from Table 1, U.S. Geological Survey).

(1995), Shearer (1999), Stein and Wysession (2003), and Yeats et al. (1997).

Two vital signs related to seismic monitoring are **earthquake activity** and **deformation and active tectonics.** Earthquake activity can be monitored using seismographs; historical data can be used to identify fault zones and other likely sources of future events, and to assess earthquake hazards. Deformation and active tectonics is related to earthquake activity and generally involves mapping and surveying fault scarps or other geomorphic features, and measuring long-term ground deformation using very accurate but traditional survey techniques or GPS (Global Positioning System) monitoring. Selected methods for seismic monitoring of these vital signs are listed in Table 2. This section briefly describes each of these methods, shows some examples of their use, and provides some references for further information or examples of each.

Earthquake Activity

Monitoring Earthquake Activity

Earthquakes are recorded by seismographs. Because many seismograph stations operate around the world and automatically send their data to central locations for routine analysis, a large amount of information about earthquake activity is rapidly available online. The IRIS Seismic Monitor (http://www.iris.edu/seismon/) and the USGS earthquake site (http://earthquake.usgs.gov) are convenient sources of current earthquake lists and maps for global and regional areas. These sites also link to others with near-real-time seismograms. For more local areas, data from regional networks (accessible from http://earthquake.usgs.gov and http://earthquake.usgs.gov/regional/) are also available. Earthquake information from these locations can be easily compiled into local earthquake catalogs, maps for statistical and spatial analysis, or other purposes. Regional and local maps can be created online from the USGS earthquake catalog using the IRIS Event Search and USGS Catalog Search tools. Earthquake information for local to global areas can also be viewed and analyzed using the Seismic/Eruption software (http://bingweb.binghamton.edu/~ajones/) that includes an extensive earthquake catalog. Specialized earthquake data sets can also be imported into the Seismic/Eruption software, as illustrated in Figure 6.

For relatively little cost and effort, one can now install and operate a seismograph at any location to record small (or large) local and regional events, as well as large earthquakes from anywhere in the world. The real-time seismograph display can be linked to additional earthquake information such as a list of significant earthquakes in the area, earthquake history, seismicity maps, and other information online. The seismograph display also provides an excellent opportunity for an education and outreach program in earthquakes, seismology, tectonics and related earth science. An inexpensive and easy-to-operate seismograph for this purpose is the AS-1 seismograph (http://web.ics.purdue.edu/~braile/indexlinks/as1.htm), which is usually described as an educational seismograph, but can very effectively record earthquakes. Another excellent option is the PEPP-V seismograph (http://www.indiana.edu/~pepp/). Other commercial seismographs can also be utilized for a local seismograph station. A guide to installing a seismograph can be found at http://pubs.usgs.gov/of/2002/ofr-02-0144/ofr-02-0144.pdf. A local college or university or geological survey office may be available to provide assistance with seismograph installation or data distribution.

If three or more seismographs are installed in a local area, or a more extensive seismic network established, earthquake locations for local events can be determined from these local stations. These hypocenter determinations are potentially more accurate (depending on the characteristics of the local network and the proximity to stations in established networks) and it may be possible to detect more and smaller events that can be used to better delineate seismic source zones. Earthquake seismograms can also be used to determine principal stress directions and infer the type of faulting (normal, reverse or thrust, strike-slip). For a description of techniques for determining earthquake mechanisms (sometimes referred to as fault plane solutions), see Stein and Wysession, (2003, chapter 4). Earthquake mechanism studies have been very important in tectonic interpretations.

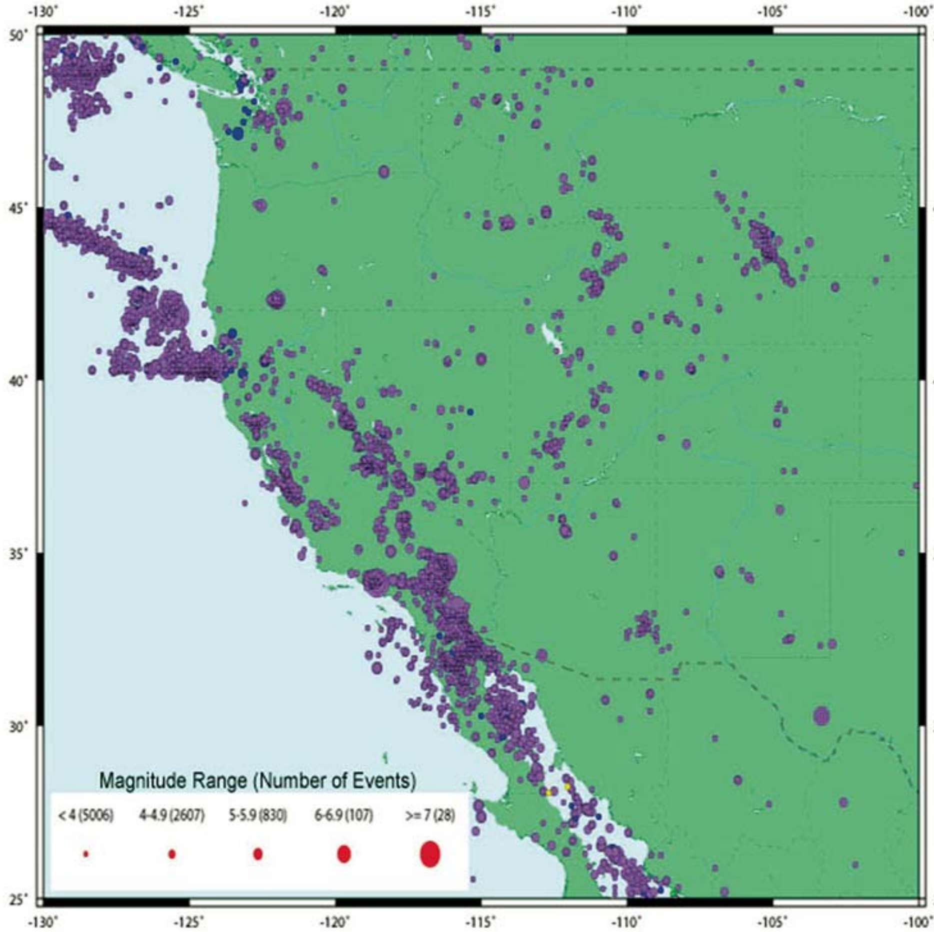

Figure 5. Map created using the IRIS Event Search tool. Earthquakes of M4+ from 1990 to 2000 were obtained from the earthquake catalog for the region shown. The epicenters were then displayed on a map using the online tool.

Local seismograph networks that include a large number of stations often utilize telemetry for rapid and efficient data transmission and collection of data for analysis at a central location. Of course, installing and operating such a network involves the significant costs of purchasing and installing the instruments, as well as maintenance and operation, which requires substantial trained staff. An example of a regional network is the Alaska seismograph network (Fig. 7). Using stations from this network as well as other global and regional stations, extensive earthquake activity and seismicity maps for Alaska (Fig. 8) are available for analysis. A poster showing major faults and associated significant earthquakes in Alaska can be viewed at http://www.aeic.alaska.edu/html_docs/images/earthquakes_in_alaska.jpg.

Analysis and Statistics of Earthquake Activity

Earthquake data for a local area from a local seismograph network, or online data from regional or global networks can be analyzed at very low cost and effort. Analysis can determine frequency of occurrences, including a frequency-magnitude diagram, an earthquake catalog, and a list of notable earthquakes.

If a local seismograph or network is available, one can also maintain a catalog of recorded events and an archive of seismograms. With a little extra effort, seismicity maps of the local area can be prepared (see method 1, above) and compared with fault maps and other geological and geophysical maps for tectonic interpretation. An online tool for accessing Quaternary fault maps for many areas of the United States is available at http://earthquake.usgs.gov/regional/qfaults/. The earthquake activity and tectonic interpretations for local areas can be compared with predicted plate motions from global plate motion models at http://sps.unavco.org/crustal_motion/dxdt/nnrcalc/.

Analysis of Historical and Prehistoric Earthquake Activity

Historical earthquake activity is an interesting characteristic of many areas that can be used to assess future earthquake probabilities and hazards, and to relate to local geological features. In some cases, prehistoric earthquake records may be accessible, which can extend the record of earthquake activity.

For most areas, it is relatively easy to compile a record of historical earthquake activity online. Earthquake catalog searches (described above) can be used to obtain hypocenter, origin time, and magnitude information for any local area. These data are reasonably complete and accurate back to 1973, and generally good even back to 1960. There are also global data files of significant

TABLE 2. SELECTED METHODS FOR SEISMIC MONITORING

Methods	Level*
Monitoring earthquake activity (earthquake origin times, locations, magnitudes, maintain local earthquake catalog)	
a. Internet access to data from global, national, or regional seismograph networks	
b. Operate local seismograph station (educational seismograph, research-quality seismograph)	1
c. Operate seismograph network (3 or more stations, educational or research-quality seismographs; earthquake detection and location including the possibility of recording microearthquakes that may not be recorded by other networks, more accurate determination of hypocenters, and analysis of earthquake mechanisms)	1,2 2–3
Analysis and statistics of earthquake activity (determine local frequency of occurrence, maintain earthquake catalog and seismograph archive, prepare seismicity maps, identifying earthquake sequences, comparison of seismicity maps with other information)	
a. Determine local area frequency of occurrence (table and frequency-magnitude graph), compile catalog of events, notable events (significant magnitude, felt, damage or effects, swarm or sequence)	1
b. Maintain seismogram archive, prepare local and regional seismicity maps and compare with fault maps, geologic maps, volcanic or hydrothermal features, other geophysical data (such as gravity and magnetic maps that may indicate faults or other significant structures), analyze cause of earthquakes in relation to existing local and regional geology and tectonic models and plate motions	2
Analysis of historical and prehistoric earthquake activity (analysis of catalogs, maps, accounts, evidence of earthquake effects)	
a. Prepare and analyze catalogs, maps, and accounts of historical earthquake activity; develop earthquake history (earliest account and records, largest magnitude, list of significant events, etc.)	1
b. Investigate prehistoric earthquake activity, Native American accounts	
c. Investigate prehistoric earthquake activity, paleoseismology investigations (trenching, seismic imaging of faults, analysis of faulted landforms, mapping fault exposures), evidence of fault effects (fault scarps, liquefaction, earthquake-induced landslides, ground failure, creep, vertical movements, tilt, etc.)	2 2–3
Earthquake risk estimation	
a. Evaluation of seismic source zones and risk maps from published sources and Internet, preparation of local risk map	1
b. Microzonation (local seismic sources, site effects that could produce amplification of seismic waves, maps of sediment thickness and properties), prediction of possible ground motion (acceleration, intensity of shaking, and effects)	2
Geodetic monitoring, ground deformation (precise measurements of position of selected locations, made at two or more times, used to calculate deformation of the ground related to ongoing tectonic, geological, or other processes)	
a. Plate motions predicted from geodetic models available on Internet	1
b. Calculation of deformation rates from earthquake effects (surface rupture, ground failure, creep)	2
c. Geodetic surveying (permanent or campaign Global Positioning System (GPS) measurements, leveling surveys, strain meter, tilt meter, satellite radar interferometry)	3
Geomorphic and geologic indications of active tectonics (geologic mapping of landforms, topography, and other features may indicate recent tectonic control suggesting active tectonic processes)	
a. Topographic features (scarps, mountain fronts, sag ponds, coastal landforms, etc.), locations of natural springs and hydrothermal features, analysis of river drainage patterns, evidence of vertical movements, tilting of lake levels	2–3

*Levels: 1—relatively simple and low cost methods; 2—methods that require moderate effort, some specialized training and experience, and modest cost; 3—methods that require significant effort, expertise, and cost.

events for the past 2000 or more years. The older earthquake information is much less complete, relies on non-instrumental estimates of magnitude (using felt reports, where available), and usually includes only larger events. Several historically significant publications on U.S. earthquakes and earthquake histories of each state can also be found on the USGS earthquake site. Several, older significant events (such as the 1811–1812 New Madrid earthquakes, the 1906 San Francisco earthquake, the 1959 Hebgen Lake earthquake, and the 1964 Alaska earthquake) have one or more publications in journals that focus on the specific event and previous earthquake history. Maps of historical earthquake data can be produced using the online tools in the USGS catalog search and using the Seismic/Eruption software (or other available mapping programs, such as geographic information system [GIS] software or Google Earth); the data is imported into the program with the desired area and time window. Instructions for using the Seismic/Eruption program for such purposes are available in the program help files and online at http://web.ics.purdue.edu/~braile/edumod/svintro/svintro.htm.

In some areas, additional earthquake information may be available from Native American accounts. Such accounts may have already been compiled and published, but some could require original research efforts. Of course, these accounts are incomplete, as they only include felt events and events close to where people lived at that time. Although researching possible Native American accounts of prehistoric earthquake activity would likely be a time-consuming project, it may be of interest to some people as it combines cultural, historical, and scientific studies.

Prehistoric earthquake information can often be obtained from specific geological studies of earthquake effects. These include studies of fault scarps, trenching fault exposures to reveal

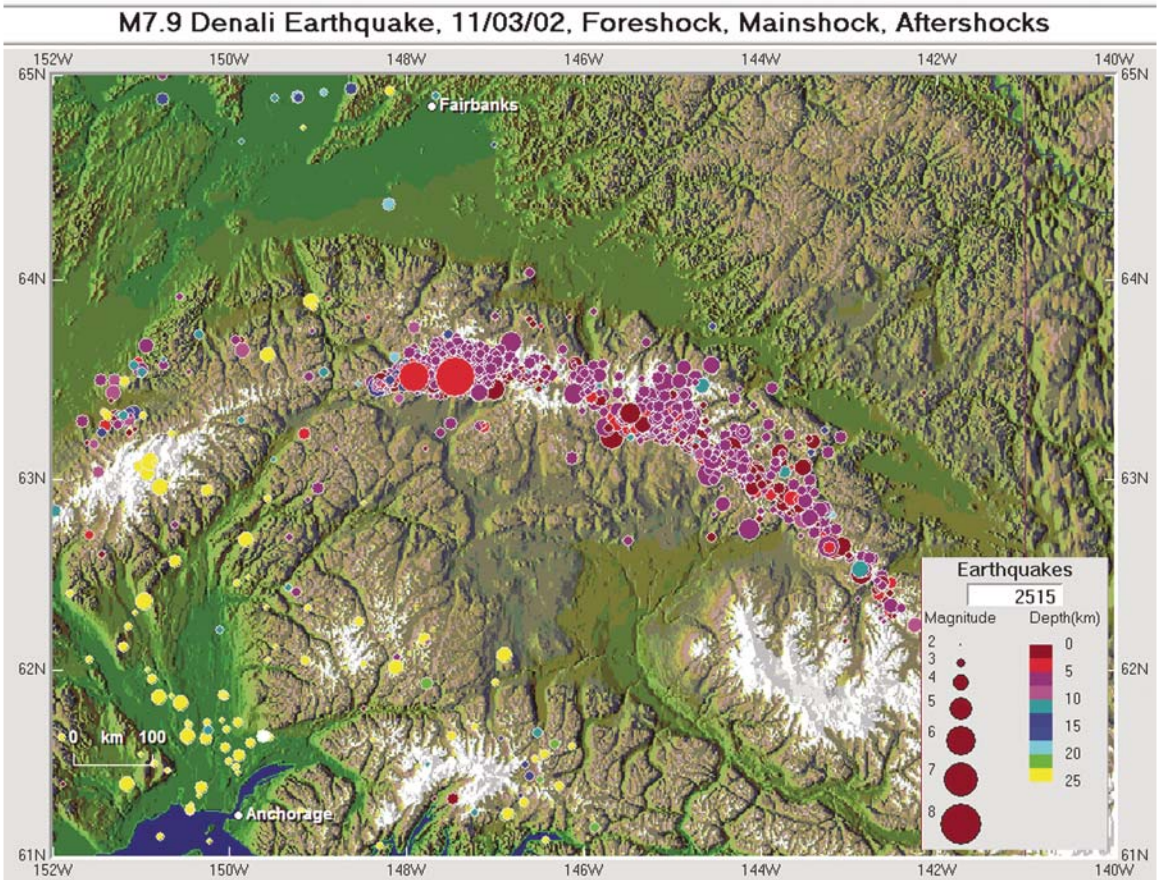

Figure 6. Earthquakes associated with the 3 November 2002 M7.9 Denali event displayed with the Seismic/Eruption software. The earthquake information (hypocenters, origin times and magnitudes) for events of M2.5+ from 1 October 2002 to 30 October 2003 were obtained by catalog search from the U.S. Geological Survey earthquake Web site. The data were then imported into the Seismic/Eruption program and displayed on the software's topographic relief map for the Denali earthquake view. The M7.9 mainshock epicenter (large dot) and the 23 October 2002 M6.7 foreshock epicenter (smaller dot to the west of the mainshock epicenter) have been highlighted in this view. Most of the other epicenters visible on the map are aftershocks that occurred along the area of the Denali fault that ruptured during the mainshock event.

ancient fault offsets that can sometimes be dated, using leveling or other survey techniques to identify deformed surfaces or landforms that may have been produced by earthquake movements, and using geophysical studies of a fault zone to determine its rupture history. These studies are often called **paleoseismology** and usually require extensive and very detailed field studies by experienced personnel. However, paleoseismology offers the potential to identify the most significant events in the recent past and therefore significantly improve the earthquake record, particularly the frequency of occurrence of the largest events in a local area. Further information on paleoseismology and the methods mentioned here are in Yeats et al. (1997) and Keller and Pinter (2002).

Earthquake Risk Estimation

Earthquake risk is usually evaluated using the historical seismicity record that provides information on the probability of occurrence (such as the frequency-magnitude relation for the area) of earthquakes of various magnitudes, and sometimes, an estimate of the maximum magnitude earthquake that is likely to occur. Estimates of maximum magnitude can also utilize the prehistoric record and an evaluation of the faults in the area, especially the length and depth extent of relatively continuous faults. When detailed information about near-surface geology is available, the risk estimation may also include estimations of ground motion and of anticipated effects on buildings, roads, and other structures.

Detailed earthquake hazard maps have been prepared for the United States and most of the world. The USGS has a very useful site (http://earthquake.usgs.gov/research/hazmaps/) that has links to these maps and other information about earthquake hazards. This site also contains an earthquake hazard mapping tool. A latitude and longitude range (within the United States) can be entered, and the tool will prepare a hazard map for that area. The

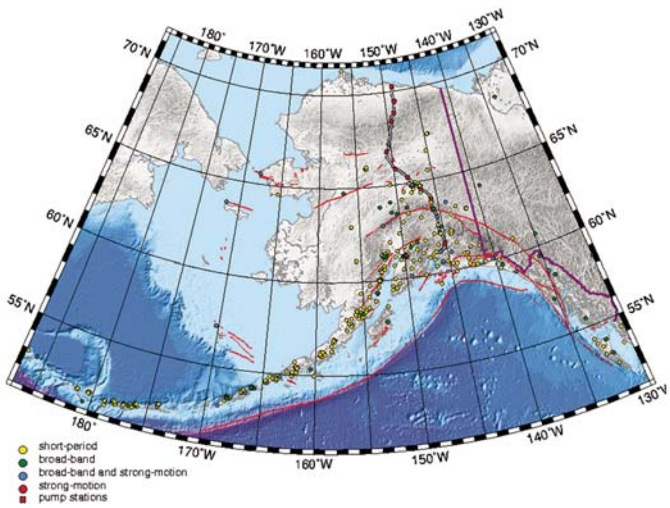

Figure 7. Seismograph stations in Alaska (http://www.aeic.alaska.edu/Seis/maps/map_of_stations.html).

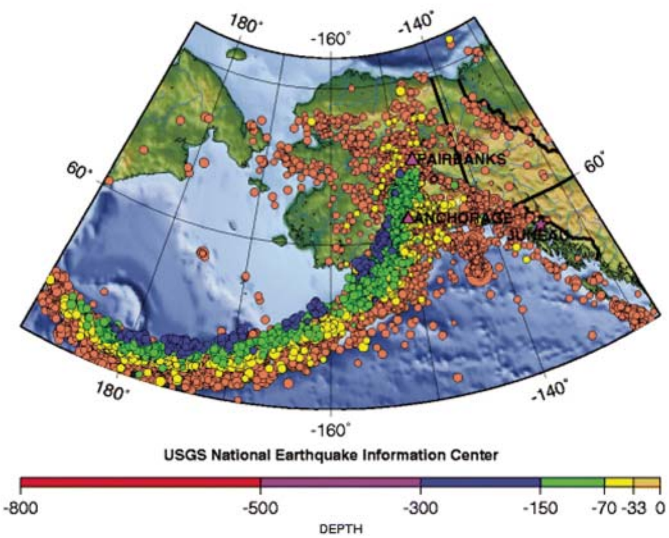

Figure 8. Seismicity of Alaska, 1990–2001, from the U.S. Geological Survey (http://earthquake.usgs.gov/regional/states.php?old=alaska/alaska_seismicity.html).

hazard maps are usually displayed as contour diagrams with the Peak Ground Acceleration (**PGA**) and the probability of its being exceeded in a specified time period (usually 50 years). With this tool, it is very easy to produce an earthquake risk map of any area in the United States.

If a more detailed and complete analysis of earthquake risk is desired for a specific area, it is possible to perform a hazard assessment involving analysis of local and regional seismicity (locations of seismic source zones, probabilities of occurrence of various magnitude events, estimation of the maximum likely magnitude, and detailed mapping of near-surface materials). However, a detailed risk assessment involves considerable effort and should be performed by experienced persons. Some local areas of the United States have already been specifically studied for earthquake risk; detailed maps for these areas are available at the USGS Web site listed above.

Deformation and Active Tectonics

Geodetic Monitoring, Ground Deformation

Geodetic monitoring is often performed to determine plate motions and current (active tectonic) ground deformation for a given area. There are a number of methods available for this purpose, including precise leveling and surveying, strain and tilt meter recording, detailed geologic mapping of active tectonic features, GPS (Global Positioning System) monitoring, and satellite techniques such as satellite laser ranging and satellite radar interferometry. Recently, GPS and satellite techniques have become very popular due to improved technology and computer processing capabilities. Effective application of these methods generally requires multiple observations over fairly long periods of time. A useful summary of these techniques and examples of applications can be found in Keller and Pinter (2002).

Information about potential ground deformation related to plate motions is available online at http://sps.unavco.org/crustal_motion/dxdt/nnrcalc/. This tool allows one to determine a crustal motion (velocity) estimate for any location; velocity is calculated from derived global or regional plate velocity models. Maps of global and regional GPS results can also be generated at the Jules Verne Voyager site at http://jules.unavco.org/Voyager/Earth.

Detailed mapping of fault offsets and other earthquake effects can be used to determine average deformation rates if accurate dating of events can be determined. However, such features may not be present, or it may not be possible to date the movements. Detailed mapping for determination of ground deformation involves significant effort and experienced persons. Additional information on these techniques and examples of their application can be found in Yeats et al. (1997) and Keller and Pinter (2002).

Geodetic surveying using one or more of the methods listed above can be performed for detailed monitoring of ground deformation that is often related to active tectonics and earthquake and volcanic activity. Because the methods used require many precise measurements, repeated observations over many years, sophisticated instrumentation and computer processing, these studies are relatively expensive and are usually performed by experts as part of an extensive, long-term research program. An example of results of satellite radar interferometry for the Yellowstone area is shown in Figure 9.

Geomorphic and Geologic Indications of Active Tectonics

Many geologic processes and landforms are affected by earthquakes and fault activity. Active faults often are visible as fault scarps, topographic breaks, and alignment of springs, lakes or sag ponds, and hydrothermal features. Faults also cause topography, such as in fault-bounded valleys, and produce uplift,

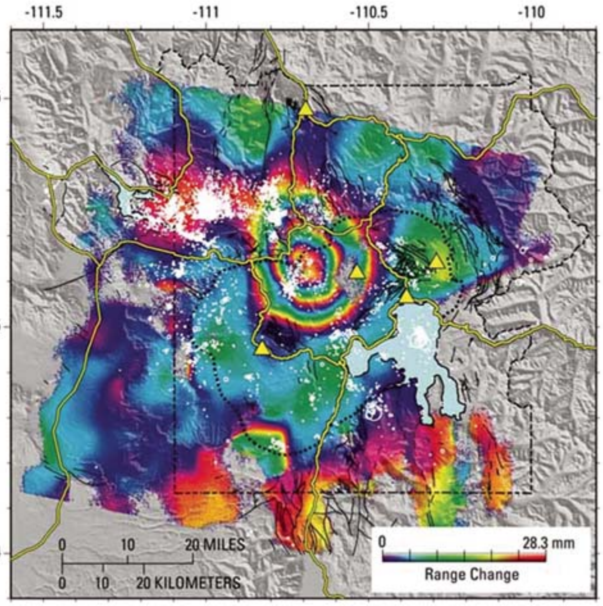

Figure 9. InSAR image of the Yellowstone area from the U.S. Geological Survey fact sheet 100-03 (2004) "Tracking Changes in Yellowstone's Restless Volcanic System" (available at: http://pubs.usgs.gov/fs/fs100-03/). Caption from the fact sheet: "A new satellite-based technique known as Interferometric Synthetic Aperture Radar (InSAR) allows direct and precise measurement of the vertical changes in ground level. This InSAR image of the area around the Yellowstone Caldera (dotted line) shows vertical changes during the 4-year period 1996–2000. The ringed pattern centered northwest of Yellowstone Lake is a prominent area of dome-shaped uplift. Each complete cycle of colors in the color bands represents a little more than one inch (28.3 mm) of vertical change. Yellow triangles are continuous GPS stations; white dots are locations of earthquakes in the period 1996–2000."

subsidence and tilt, and control drainage patterns. Most of these features can be effectively identified and interpreted by detailed geological mapping. If the features are prominent, mapping and associated studies can be relatively straightforward. More subtle or complex effects require extensive study and a multidisciplinary approach, often involving geological interpretation, precise topographic surveying and leveling, collection and interpretation of geophysical data, and age dating. A useful summary of geomorphic and geological methods for study of fault zones, active tectonics, and related earthquake features is provided by Keller and Pinter (2002).

Summary and Recommendations for Seismic Monitoring

Seismic monitoring in and around national parks is used for earthquake, tectonic, and geological research, earthquake hazard assessment, and public education. With only a small effort, one can investigate the earthquake history and hazards of a national park and surrounding areas. In both active and inactive areas, an educational seismograph can be used to monitor local, regional, and global earthquake activity. An operating seismograph is always an attraction for park visitors. More extensive seismic monitoring and analysis of earthquake effects, tectonic activity and earthquake risk requires significant effort, costs and expertise, and may require installation of a seismograph network and other instrumentation.

A few national parks (Yellowstone, Grand Teton, Mount Rainier, Mount St. Helens, and Hawaii Volcano) have seismograph networks or are part of regional seismograph monitoring networks. Parks in California, Nevada, Utah, Washington, Oregon, Alaska, and Puerto Rico are monitored by state and regional seismograph networks. A listing of regional seismograph operators and cooperators is available at http://earthquake.usgs.gov/research/topics.php?areaID=12, with additional information about seismic monitoring and the earthquake activity in these regions. Seismographs operating in national parks in low seismicity areas are generally installed for educational purposes and can generate public interest from recording regional or global earthquake activity. Finally, a list of seismic monitoring methods not discussed in this chapter is given in Table 3.

STUDY DESIGN

In considering a plan for seismic monitoring of a national park (or other local area), the specific or unique features of the park, the level of the local earthquake and tectonic activity, and the goals should be evaluated. For example, some areas are very seismically active (or are adjacent to seismically active areas) and have prominent features (such as fault-related topography, volcanic activity, or springs and hydrothermal activity) related to earthquakes and active tectonics. In these areas, one should also consider the earthquake hazard and emergency management response objectives of seismic monitoring. Scientific research designed to better understand the earthquake activity and geological evolution of the area may also be important. Assistance in seismic monitoring design and objectives may be obtained from the USGS and academic researchers already in cooperation with a specific park. Additional geology and tectonic information on national parks can be found in Harris et al. (2004) and Lillie (2005).

Some areas may not display significant local earthquake activity but may still be selected for seismic monitoring because of visitor interest and educational objectives. As mentioned previously, seismic monitoring and a visible seismograph display can be very effective in generating visitor interest in park features and in the geology of the area, and can be used as a key element of an education program. In both seismically active and relatively inactive areas, at least one educational seismograph for earthquake monitoring and display is a very cost-effective approach to beginning (or augmenting) a seismic monitoring program.

Plans for a local seismic monitoring program must also include consideration of the cost of the program, and the resources and personnel available to be devoted to the effort. Several cost-effective methods for seismic monitoring studies that do not require substantial personnel or experts to conduct the studies are listed in Table 2 and described above. Of course, more extensive

TABLE 3. OTHER SEISMIC MONITORING METHODS NOT DISCUSSED IN DETAIL

Methods	Level*
Tsunami hazard (applies to low elevation, coastal areas, tsunami warning system in place in many area of the United States that are at risk)	
a. Connect to tsunami warning system	1
b. Investigation and mapping of tsunami deposits to determine frequency of past tsunamis that have affected the area	2
Earthquakes caused by human activity (applies to areas where specific human activities are present, such as crustal loading [mostly reservoir filling], deep well injection or removal of fluids, mining that reduces the confining pressure of rocks adjacent to the mined areas, rock bursts, large explosions)	
a. Monitoring and analysis methods are similar to those described in Table 2.	1–3
Forecasting earthquakes (analysis of earthquake statistics, recurrence intervals, earthquake cluster and swarm activity, and aftershock sequences to forecast future events)	
a. Monitoring and analysis methods are similar to those described in Table 2.	1–3

*Levels: 1—relatively simple and low cost methods; 2—methods that require moderate effort, some specialized training and experience, and modest cost; 3—methods that require significant effort, expertise, and cost.

and sophisticated seismic monitoring studies will require greater resources and usually will need to be performed by experienced persons or experts in the particular method selected.

The EarthScope program presents a unique opportunity for parks and other resources and organizations to be involved in earthquake and earth science education and research. Currently, EarthScope has deployed a large array of seismographs over a region in the western United States. The array will be progressively shifted to the east to provide coverage of the entire contiguous United States. The deployment is aimed at investigating the structure and evolution of the continent. The current status of the instrumentation deployment can be viewed at: http://www.earthscope.org/current_status/. In addition, an extensive array of GPS instruments is also being deployed, primarily in the western United States, to study the tectonics and deformation associated with the plate boundaries of that area. Temporary, portable arrays are also being utilized in research projects focused on specific geological features or areas. Data and results from these programs are available and can be used in association with local seismic monitoring and other geological and geophysical studies to enhance our knowledge of these areas and better educate the public. In some cases, it has been possible to deploy EarthScope instruments in national parks and to design specific experiments related to the earth science features in parks. Additional opportunities will exist as additional instruments are deployed and the seismograph array progresses across the United States. Further information on the EarthScope can be found at the EarthScope program Web site (http://www.earthscope.org/) and in Meltzer et al. (1999) and Meltzer (2003).

CASE STUDIES OF SEISMIC MONITORING

As an example of seismic monitoring in a national park, this section describes a study and monitoring program focused on the Joshua Tree National Park area; this study mostly uses data available online. Because Joshua Tree National Park is near a very seismically active area of southern California, earthquakes within or near the park present a significant seismic hazard. Strong ground shaking within the park could damage structures or trigger landslides or rock fall. To view the earthquake activity in and near the park, we used a catalog search and the Seismic/Eruption software to produce a map of seismicity from 1990 to 2004 (Fig. 10). Most of the epicenters are outside of the park, associated with the San Andreas and related faults to the west; nevertheless, large earthquakes on these faults can cause significant shaking within the park (Fig. 11).

Many of the earthquakes shown on the seismicity map (Fig. 10) are aftershocks associated with the M7.4 Landers and M6.4 Big Bear earthquakes that occurred on 28 June 1992. The north-trending zone of epicenters just to the west and north of the Joshua Tree National Park boundary is the area of the Landers aftershocks. The cluster of epicenters near the northwest corner of the maps is the Big Bear epicenters.

A simple and useful statistical analysis of earthquake activity near Joshua Tree National Park can be completed by preparing a frequency-magnitude plot using the earthquake data shown in Figure 10. To obtain the data for the frequency-magnitude plot, one can sort the earthquake catalog by magnitude for the geographical area and time period selected, and then count the events within each magnitude range. The sorting and counting can easily be accomplished in a spreadsheet program such as Excel. Alternatively, if the data are imported into the Seismic/Eruption program, the counter within the software can be used to sequentially count the number of events above a specified magnitude cutoff.

The results of the frequency-magnitude analysis for the Joshua Tree National Park and surrounding area are shown in Figure 12. A straight line has been fitted to the central data points illustrating that the frequency-magnitude relation for this area is approximately linear, similar to that shown for the worldwide earthquakes in Figure 4. The observed number of earthquakes for magnitudes of 2 and above is low because not all small earthquakes are well recorded (or their magnitudes determined) by the available seismographs in the area. Also, the data point for M+ = 7 does not fall on the line, probably because the time period selected (15 years) was not long enough to accurately determine the rate of earthquake activity for large, relatively rare events. For example, an M7+ event occurred within the selected time

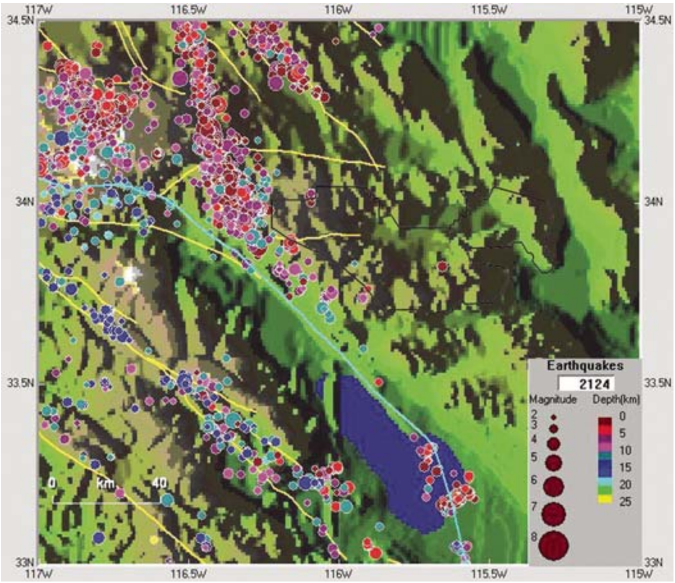

Figure 10. Earthquake epicenters in the Joshua Tree National Park area (park boundaries shown by thin black outline near center of map). Light lines are mapped faults. The earthquake information (hypocenters, origin times and magnitudes) for events of M2.0+ from 1 January 1990 to 31 December 2004 were obtained by catalog search from the U.S. Geological Survey earthquake Web site. The data were then imported into the Seismic/Eruption program and displayed on the software's topographic relief map (topo30) using the "make your own map" tool.

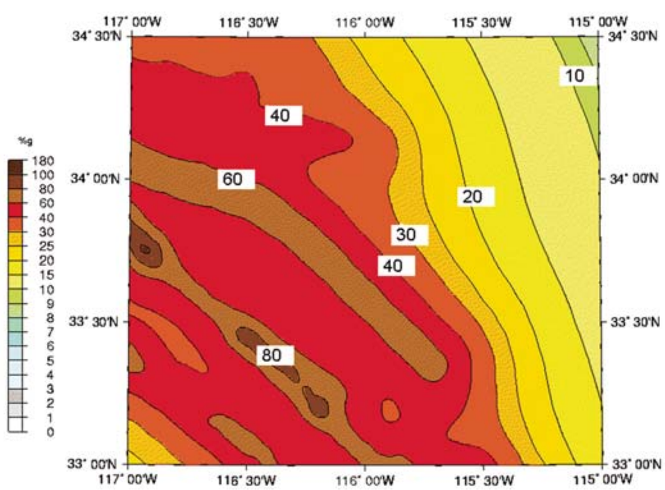

Figure 11. Earthquake risk map for the Joshua Tree National Park area (area shown is the same as in the seismicity map in Fig. 10). The contours show estimated peak acceleration (%g) with a 10% probability of being exceeded in 50 years. Map generated with the U.S. Geological Survey custom map tool on the earthquake hazard map site http://earthquake.usgs.gov/hazmaps/interactive/.

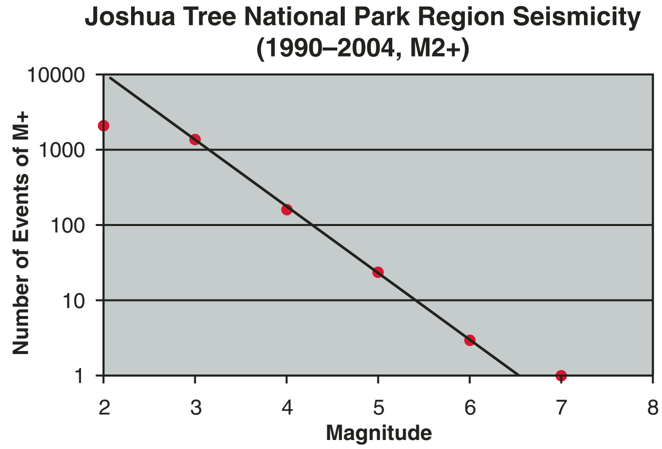

Figure 12. Frequency-magnitude plot for the earthquake data shown in Figure 10. To obtain an estimate of the number of events per year for any specified magnitude, divide the value on the y-axis by 15 years.

period, but if we had chosen a 30-year time period, it is likely that all of the other data points (numbers of events) would be approximately twice as large (and the M7+ data point might still be equal to 1).

The frequency-magnitude relation can be used to estimate the recurrence interval for a given magnitude earthquake. For example, for a magnitude 6 or above event, the number in 15 years is 3, and this data point falls on the linear portion of the frequency-magnitude relation. This suggests that the resulting recurrence interval should be reasonably reliable. Because there were three M6+ earthquakes in 15 years (in the area shown in Fig. 10), the frequency of occurrence for M6+ earthquakes for the selected area averages about one event every five years.

Additional statistical analysis, compilation of a fairly complete catalog and list of notable events, analysis of historical and prehistoric earthquake records, and an earthquake history could be easily developed for Joshua Tree National Park and the surrounding area. Further, earthquake recording (and selected additional studies listed in Table 2) within the park using available seismograph data from the ANSS or California state network (several seismograph stations operate in or very near the park; see http://www.data.scec.org/stationinfo.html for a station map), or from an educational seismograph station installed in Joshua Tree National Park, could be initiated to enhance seismic monitoring in the area.

Seismic monitoring, earthquake activity, and related tectonic and volcanic activity in the Yellowstone National Park area have been extensively studied by University of Utah and USGS scientists and others, and provides another example. A seismograph station map for the Yellowstone National Park area is shown in Figure 13. Earthquakes in the area have been recorded by a Yellowstone National Park seismograph network since the 1970s. Today, many of the stations are digitally recorded and transmit their data in near real time to a central recording site. Near-real-time data

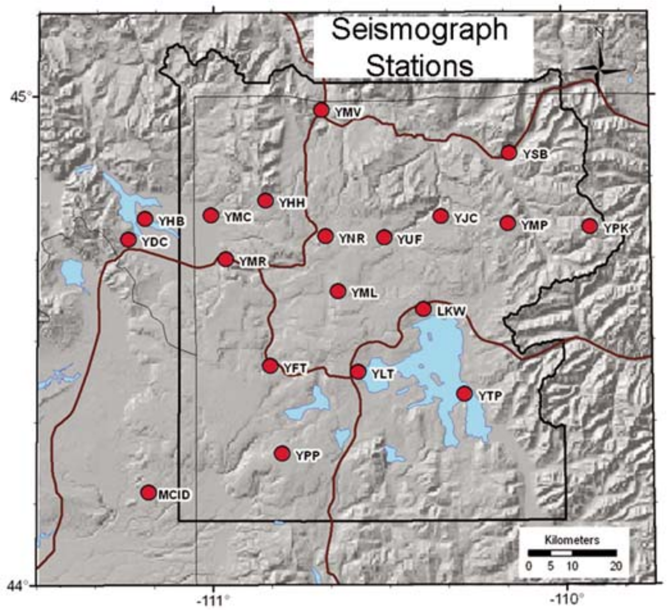

Figure 13. Seismograph stations in the Yellowstone National Park area (2006). From http://www.seis.utah.edu/helicorder/yell_webi.htm.

(seismogram/helicorder display) for many of these stations can be viewed at http://www.seis.utah.edu/helicorder/index.html.

Earthquake epicenters for 1973–1996 for the Yellowstone National Park area are shown in Figure 14. The epicenters are generally clustered within and near the Yellowstone **caldera** (a large bowl-shaped depression or crater formed by collapse into a voided magma reservoir during a volcanic eruption). To the north and west of the caldera, the epicenters display an approximately west-east trend near the epicenter of the 1959 M7.3 Hebgen Lake earthquake. Within the caldera region, the epicenters are generally aligned in a north-northwest direction parallel with the general trend of most of the mapped Quaternary faults (Fig. 14). The nearly continuous seismic monitoring by the local seismograph network operated by the University of Utah, in cooperation with Yellowstone National Park and the USGS, has been particularly important in obtaining accurate locations of epicenters (and depth of focus) of the frequent microearthquakes that occur in the area. The detection ability of the local network, as compared to that from global and regional stations, provides the ability to detect microearthquakes and accurately locate hypocenters. The hypocentral patterns correlate with the mapped faults (Fig. 15) and a shallowing of earthquake depths under the Yellowstone caldera that is probably caused by high temperatures in the crust beneath the caldera (Fig. 16). The detailed earthquake monitoring of the local network has also allowed analysis of earthquake swarms that are characteristic of volcanic systems; further, the monitoring has helped determine earthquake mechanisms that yield important information on the directions of principal stresses and the type of active faulting in the area (Waite and Smith, 2002).

A frequency-magnitude plot for M2+ earthquakes from 1975 to 2004 for the Yellowstone area is shown in Figure 17. The

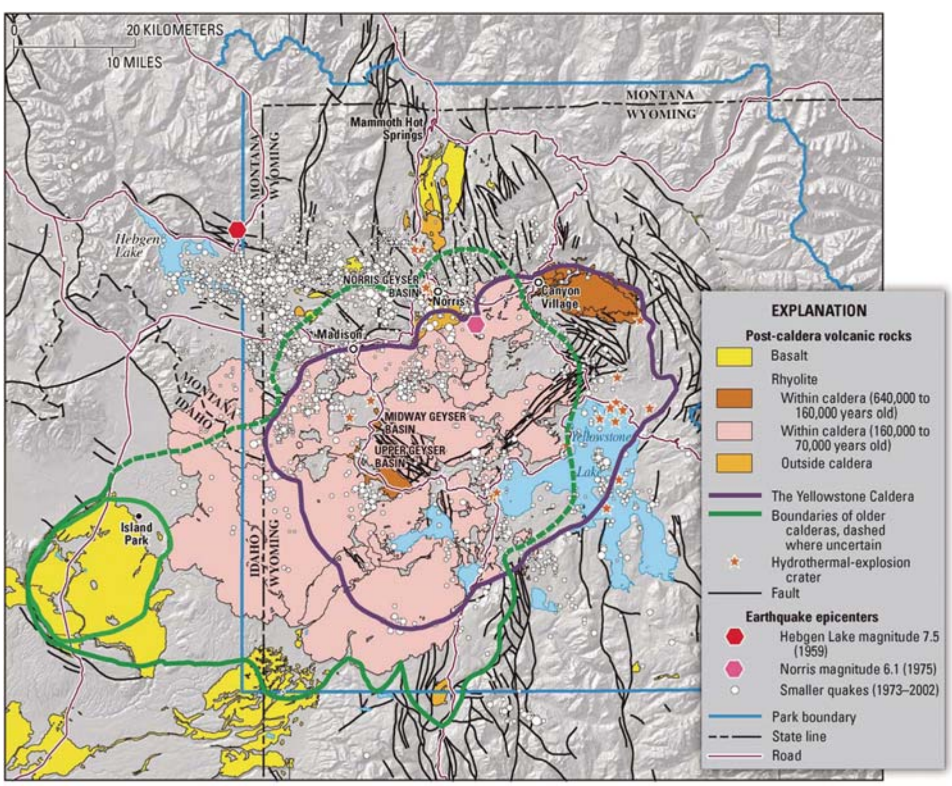

Figure 14. Earthquake epicenters (dots; size of dot is proportional to magnitude), volcanic vents, normal faults, caldera boundaries and volcanic rocks of the Yellowstone National Park area; light line is caldera boundary (from http://pubs.usgs.gov/fs/2005/3024/).

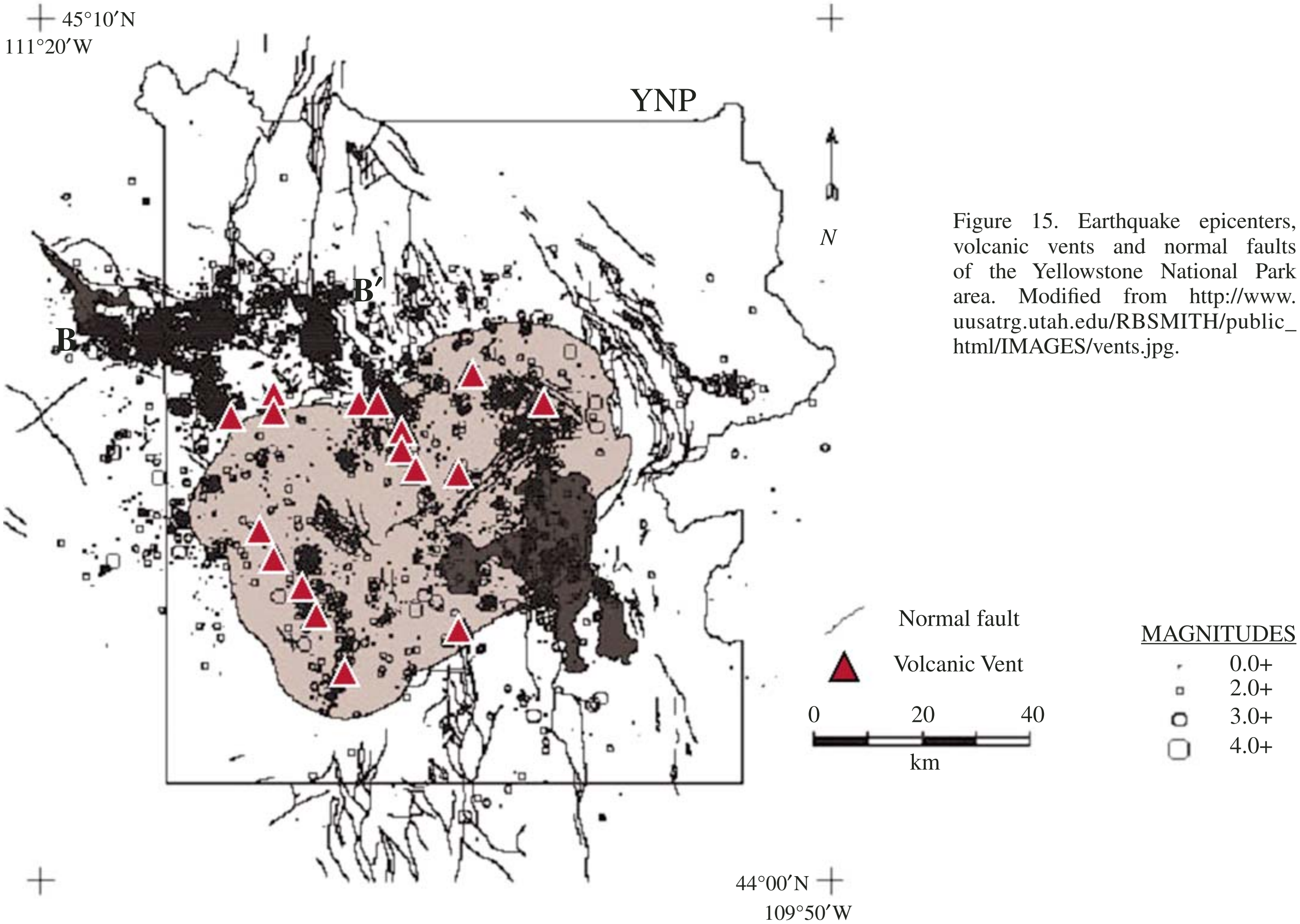

Figure 15. Earthquake epicenters, volcanic vents and normal faults of the Yellowstone National Park area. Modified from http://www.uusatrg.utah.edu/RBSMITH/public_html/IMAGES/vents.jpg.

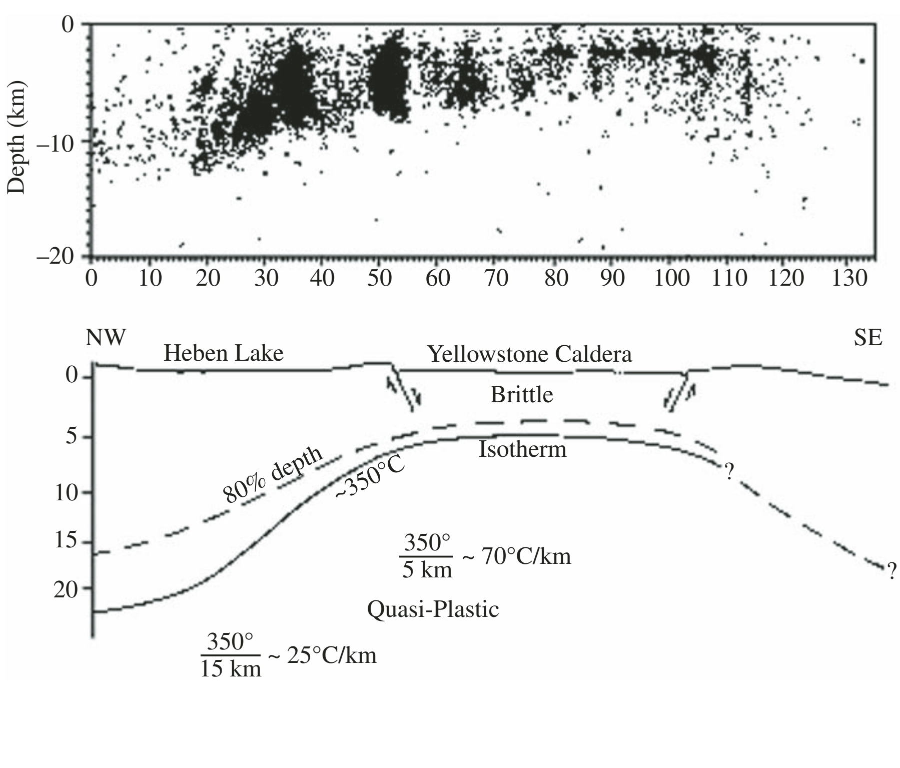

Figure 16. Northwest to Southeast cross section (upper diagram) view of earthquake depths through the Yellowstone caldera. The lower cross section diagram is a schematic illustration of interpreted decrease in the thickness of the brittle crustal layer due to high temperatures beneath the caldera. From: http://www.uusatrg.utah.edu/RBSMITH/public_html/IMAGES/19-36ysxs.jpg.

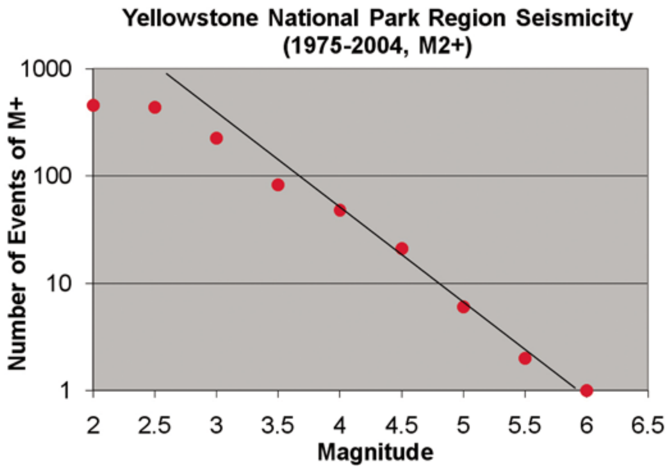

Figure 17. Frequency-magnitude plot for the Yellowstone National Park region (latitude 44°N to 45.1°N, longitude −111.3° to −109.8°). To obtain an estimate of the number of events per year for any specified magnitude, divide the value on the y-axis by 30 years.

data used to prepare this figure were obtained by a catalog search on the USGS earthquake Web site. The results are similar to those in the previously discussed Joshua Tree National Park area. The frequency-magnitude relation for the Yellowstone National Park area (Fig. 17) displays an approximately linear trend for magnitudes of ~3 or greater, suggesting that the earthquake catalog used was not complete for smaller magnitudes. Recurrence intervals can be inferred from the frequency-magnitude plot. For example, there were six M5+ events in the 30 years of earthquake activity considered here, indicating that there should be an average of about one M5+ earthquake in the Yellowstone National Park area about every five years.

Several geodetic and crustal deformation studies have been performed in the Yellowstone National Park area, including the GPS study by Meertens and Smith (1991) and survey and leveling surveys. The previously mentioned satellite radar interferometry study (Fig. 9) also shows that the Yellowstone area is a very active region and is associated with significant vertical movements.

For additional information on the earthquakes, volcanic and tectonic activity of the Yellowstone area, see Smith and Arabasz (1991), Smith and Braile (1994), Smith and Siegel (2000), and the USGS fact sheet 2005-3024 (2005) "Steam Explosions, Earthquakes, Volcanic Eruptions: What's in Yellowstone's Future?" available at http://pubs.usgs.gov/fs/2005/3024/.

TABLE 4. SUMMARY OF SEISMIC MONITORING METHODS

Methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Monitoring Earthquakes					
a. Internet access to data	Volunteer	No	$	Individual	Medium
b. Local seismograph station	Volunteer	Yes	$	Individual	High
c. Operate seismograph network	Expert	Yes	$$$	Group	High
Analysis and statistics of earthquake activity					
a. Frequency of occurrence	Scientist	No	$	Individual	Medium
b. Seismogram archive, seismicity maps	Scientist	Yes	$$	Individual	High
Analysis of historical and prehistoric earthquake activity					
a. Catalog, maps, and accounts of historical earthquake activity	Scientist	No	$	Individual	Medium
b. Investigate prehistoric earthquake activity, Native American accounts	Scientist	No	$	Individual	Medium
c. Investigate prehistoric earthquake activity, paleoseismology, evidence of earthquake effects	Expert	Yes	$$$	Individual	High
Earthquake risk estimation					
a. Seismic source zones, risk maps from published sources and Internet	Scientist	No	$	Individual	Medium
b. Microzonation, prediction of possible ground motion	Expert	No	$$$	Individual	High
Geodetic monitoring, ground deformation					
a. Plate motions predicted from geodetic models available on Internet	Scientist	No	$	Individual	Medium
b. Deformation rates from earthquake effects	Expert	Yes	$$$	Group	High
c. Geodetic surveying	Expert	Yes	$$$	Group	High
Geomorphic and geologic indications of active tectonics					
a. Topographic features, springs and hydrothermal features, river drainage, vertical movements, tilt	Expert	Yes	$$$	Group	High

*Cost (US$): $ = <$1,000; $$ = $1,000–$10,000; $$$ = >$10,000.
†Labor intensity: low = <few hours; medium = full day; high = >full day.

CONCLUSIONS

Seismic monitoring can provide extremely useful and interesting data about the dynamic Earth. Local and regional earthquake activity can be analyzed using data available online from regional, national, and global networks. Local seismic monitoring can also be augmented by installation of local seismographs. These data can be used for many purposes, including determining the frequency of occurrence of earthquake activity, evaluating earthquake risk, interpreting the geological and tectonic activity of the area, and providing an effective vehicle for public information and education.

A comparison of the seismic monitoring methods discussed here is given in Table 4. In this Table, the relative expertise, technology and instrumentation, cost, and personnel requirements for implementing the various monitoring methods are listed.

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