ShakeMap Manual

Release

C. Bruce Worden, David Wald

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CHAPTER ONE

INTRODUCTION

This ShakeMap Manual (*Worden and Wald, 2016*), is a significant update of the original (*Wald et al., 2005*) ShakeMap Manual. We employ Python document generator Sphinx, with the source under GitHub version control. The online version of the manual is available at http://usgs.github.io/shakemap.

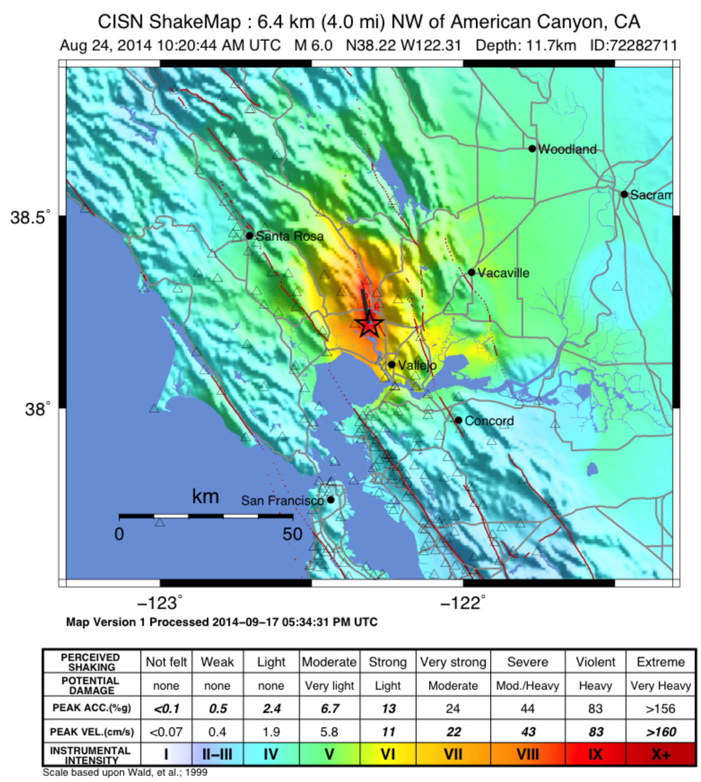


Fig. 1.1: 2014 M6.0 Napa, CA, earthquake intensity ShakeMap.

ShakeMap®, developed by the U.S. Geological Survey (USGS), facilitates communication of earthquake information beyond just magnitude and location. By rapidly mapping out earthquake ground motions, ShakeMap portrays the distribution and severity of shaking. This information is critical for gauging the extent of the areas affected, determining which areas are potentially hardest hit, and allowing for rapid estimation of losses. Key to ShakeMap's success, algorithms were developed that take advantage of any high-quality recorded ground motions—and any available macroseismic intensity data—to provide ground-truth constraints on shaking. Yet ShakeMap also utilizes best practices for both interpolating recordings and—critically—providing event-specific estimates of shaking in areas where observations are sparse or nonexistent. Thus, ShakeMap portrays the best possible description of shaking by employing a combination of recorded and estimated shaking values.

This Manual provides background on technical aspects of ShakeMap including: 1) information on the wide range of products and formats ShakeMap produces, 2) the uses of these products, and 3) guidance for ShakeMap developers and operators. Readers interested in understanding how ShakeMaps works can navigate to the *Technical Guide*. Those who want to use ShakeMap products and understand their varied forms can jump to the *User's Guide*. If your goal is to install and operate ShakeMap, see the *Software & Implementation Guide*. The *Software & Implementation Guide* also points users to the ShakeMap software distribution and Software Guide.

CHAPTER TWO

TECHNICAL GUIDE

This ShakeMap Technical Guide is meant as the definitive source of information pertaining to the generation of ShakeMaps. Many of the initial descriptions in *Wald et al. (1999a)* are outdated and are superseded by this current report. Technical users of ShakeMap should also consult the *User's Guide* for additional information pertaining to the format and range of available ShakeMap products.

Throughout this document, all parameters are italicized; specific parameters that can be configured within the ShakeMap software are indicated in parentheses. These configurable parameters are further described in the ShakeMap *Software Guide*.

2.1 ShakeMap Software Overview

ShakeMap is a collection of modules written in PERL and C. PERL is a powerful, freely available scripting language that runs on all computer platforms. The collection of PERL modules allows the processing to flow in discrete steps that can be run collectively or individually. Within the PERL scripts, other software packages are called, specifically packages that enable the graphics and much of the heavy grid-based computation. For instance, maps are made using the Generic Mapping Tool (GMT; *Wessel and Smith, 1991)*, and the Postscript output from GMT is converted to JPEG format using ImageMagick or GraphicsMagick. In the design of ShakeMap, all components are built from freely available, open-source packages.

While the PERL language is not the fastest possible way to implement ShakeMap, we note that much of the heavy computational load is handled by highly optimized programs (usually written in C) that are called from within the PERL programs. Even for networks with hundreds of stations over large regions, ShakeMap takes only a minute or so to run on a modern computer (and much of that time is spent in product generation, e.g., converting PostScript images to JPEG—something that would be very difficult to optimize further).

To enable customization for specific earthquakes or for different regions, each ShakeMap module has an accompanying collection of configuration files. For example, in these files, one assigns the regional geographic boundaries and mapping characteristics to be used by GMT, which ground motion prediction equation (GMPE) to use, where and how to transfer the maps, email recipient lists, and so on. Specific details about the software and configuration files are described in detail in the *Software Guide*.

With standardization in GIS and web application interfaces (API), several aspects of the ShakeMap system could be accomplished within GIS applications, but the open-source, freely available nature of GMT combined with PERL scripting tools allows for a flexible and readily available ShakeMap software package. Nonetheless, we do generate a number of GIS product formats for that widespread user group as described in the *User's Guide*.

2.2 Philosophy of Estimating and Interpolating Ground Motions

The overall strategy for the deployment of stations under the ANSS implementation plan relies on dense instrumentation concentrated in urban areas with high seismic hazards (*USGS, 1999*) and fewer stations in outlying areas. Based on this philosophy, and when fully deployed, maps generated in these urban regions are expected to be most accurate where the population at risk is the greatest, and therefore, where emergency response and recovery efforts will likely be most urgent and complex.

Even so, significant gaps in the observed shaking distribution will likely remain, especially in the transition from urban to more rural environments. Likewise, many critical facilities and lifelines are widely distributed, away from population centers and their dense seismic sensor networks. Thus, as a fundamental strategy for ShakeMap, we have developed algorithms to best describe the shaking in more remote areas by utilizing a variety of seismological tools. In addition to the areas without sufficient instrumentation where we would like to estimate motions to help assess the situation, and as a fail-safe backup, it is also useful to have these algorithms in place in the event of potential communication dropout from a portion of the network. The same tools are, in fact, beneficial for interpolating between observations (i.e., seismic stations) even within densely instrumented portions of the networks.

If there were stations at each of the tens of thousands of map grid points needed to adequately portray shaking, then the creation of shaking maps would be relatively simple. Of course, stations are not available for the overwhelming majority of these grid points, and in many cases grid points may be tens of kilometers or more from the nearest reporting station. The overall mapping philosophy is then to combine information from individual stations, site amplification characteristics, and ground-motion prediction equations for the distance to the hypocenter (or to the causative fault) to create the best composite map. The procedure should produce reasonable estimates at grid points located far from available data while preserving the detailed shaking information available for regions where there are stations nearby.

It should be mentioned that mathematically, or algorithmically, geospatial interpolation can take many forms. There are some good reasons to employ geospatial kriging-with-a-trend. However, the complexity of the trends (GMPE, as well as inter-event bias corrections per Intensity Measure or IM), the use of multiply-weighted strong-motion and macroseimic data, and the real-time nature of the processing require other considerations. Effectively, the approach ShakeMap currently employs for interpolation (*Worden et al., 2010*), which employs a predetermined spatial correlation function, is broadly analogous to kriging-with-a-trend mathematically. We address this possibility further in *Future Directions*.

Estimating motions where there are few stations, and then interpolating the recordings and estimates to a fine grid for mapping and contouring, requires several steps. In the following sections, we describe the process from input to final interpolated grid. Where beneficial, we illustrate the effects of key steps with example ShakeMap figures.

2.3 Recorded Ground-motion Parameters

2.3.1 Data Acquisition

ShakeMap requires estimates of magnitude, location, and (optionally, but preferably) shaking IMs at seismic stations. As such, ShakeMap has been interfaced with several types of seismic processing systems in wide use at numerous networks across the U.S. and around the world, including Antelope, SeisComP3, and AQMS. The ShakeMap system, however, is a stand-alone software package and is really a passive consumer of seismic data. In other words, the ShakeMap software itself contains no data acquisition component. It is assumed that ShakeMap earthquake source information and parametric data are packaged for delivery to ShakeMap and that that delivery will trigger a ShakeMap run. The required format is an XML format, as fully described in the *Software Guide*. Some programs are provided to convert ASCII text and other formats to the required input XML. It is assumed that station data delivered to ShakeMap are free-field sites that have been vetted by the contributing network. Each station must have stand-alone metadata describing its station location, contributing network, channel, and location code. While some additional outlier and data quality checks are performed within ShakeMap (see *ShakeMap Processing*), it is assumed that this is primarily the responsibility of the contributing seismic network.

For global and historic earthquake ShakeMap generation, we have developed scripts to preprocess various forms of seismic waveform (as well as macroseismic) data which are openly available around the world. For example, we provide a Python script getstrong.py that runs independently of ShakeMap, as described in the *Software & Implementation Guide*.

For illustrative purposes, we describe the data acquisition for the seismic system in Southern California, a component of the California Integrated Seismic Network (CISN). For perspective, as of 2015, there were nearly 800 real-time stations jointly operated with a collaboration between the USGS and the California Institute of Technology (Caltech). In addition, the California Geological Survey (CGS) contributes nearly 350 strong-motion stations in near real-time, utilizing an automated telephone dial-up procedure (*Shakal et al, 1998*), and the USGS National Strong Motion Instrumentation Program (NSMP) contributes dial-up station parameters as well, with nearly 50 stations in Southern California alone. Lastly, the "NetQuakes" program, a relatively low-cost seismograph that the USGS installs in homes, businesses, buildings, and schools, contributes close to 100 additional stations in Southern California.

Generation of ShakeMap in Southern California is automatic, triggered by the event associator of the seismic network. Within the first two minutes of an earthquake, ground-motion parameters are available from the USGS-Caltech component of the network, and within several minutes most of the important near-source CGS and NSMP stations contribute; a more complete CGS and NSMP contribution is available within approximately ten minutes of an event. Initial maps are made with the real-time component of CISN as well as any of the available dial-sites, and they are updated automatically as more data are acquired.

2.3.2 Derived Parametric Ground-motion Values

Parametric data from stations serving ShakeMap should include peak ground acceleration (PGA), peak ground velocity (PGV), and peak response spectral acceleration amplitudes (at 0.3, 1.0, and 3.0 sec). Often, parametric values are derived continuously, using recursive time-domain filtering as described by *Kanamori et al. (1999)*. Otherwise parameters are derived from post-processing as described by *Shakal et al. (1998)* and *Converse and Brady (1992)*.

ShakeMap will run successfully with no (or limited) parametric data, for example if only PGA values are available at each station. Default logic is employed to provide reasonable behavior for estimating intensities from PGA alone, bias correction, and interpolation (see following sections). Likewise, for smaller-magnitude earthquakes, spectral values can be noisy, so operators often omit the generation spectral maps below a lower magnitude threshold (about M4); this can be done with simple command-line options.

For all maps and products, the motions depicted are peak values as observed; that is, the maximum value observed on the two horizontal components of motion. Many engineers are accustomed to analyses employing the geometric mean of the horizontal peak-ground motions, but that parameter is not computed by ShakeMap. More description and justification for this strategy is given in the section *Use of Peak Values Rather than Mean*. It should be noted, however, that conversions from peak to geometric mean [or orientation-independent parameterizations (*Boore, 2010*)] are available (e.g., *Beyer and Bommer, 2006*).

2.3.3 Macroseismic Intensity

ShakeMap also (optionally) accepts input data in the form of observed macroseismic intensity (MMI, MCS, etc.). As with peak ground motion parameters from seismic stations, ShakeMap expects specific file formats (XML) and site metadata for macroseismic data (see the *Software Guide*).

Intensity data can fill important gaps where ground-motion recordings are not available, and often provide the only control in sparsely instrumented areas. This is particularly true for historic earthquakes, for which macroseismic data provide important constraints on shaking intensities. As later discussed, the ShakeMap Atlas (*Allen et al., 2008*, *2009a*; *Garcia et al., 2012a*) is a collection of important historic earthquake shaking maps which are now widely used for scientific analyses and for loss model calibration (e.g., *Wald et al., 2008*; *Jaiswal and Wald, 2010*; *Pomonis and So, 2011)*.

The most common source for immediate post-earthquake intensity data is the USGS's "Did You Feel It?" (DYFI) system (*Wald et al., 2011*), though similar systems are available in several countries. However, traditionally assigned intensities may be used as well. DYFI data can be programmatically retrieved from the USGS's database and formatted for ShakeMap input using the ShakeMap program *getdyfi*, making it especially easy to incorporate into the ShakeMap data input stream.

Macroseismic intensity data can also be an important constraint on peak ground motions, since ground motion amplitudes can be derived from intensity through the use of a suitable Ground-Motion/Intensity Conversion Equation (GMICE). Because a GMICE represents a statistical (probabilistic) relationship, the conversion to and from intensity has a higher uncertainty than direct ground-motion observation. ShakeMap accounts for this higher uncertainty by down- weighting converted observations in the interpolation process, as discussed in the *Interpolation* section.

A variety of GMICEs are available with the ShakeMap software distribution, both for MMI—based on *Wald, et al. (1999b)*, *Worden, et al. (2012)*, and *Atkinson and Kaka (2007)*, among others—and for MCS—based on *Faenza and Michilini (2010)*. Operators are encouraged to explore the need to develop their own relationships based on data covering their own operational area as GMICEs have been shown to have regional dependencies (e.g., *Caprio et al., 2015*). A complete list of GMICEs currently employed by ShakeMap is provided in the *Software Guide*.

We have implemented a convention for maps and regression plots that seismic stations are represented with triangles and macroseismic data are depicted with circles (see Figure 2.1, for example). This convention is forward-looking: not all seismic networks were currently following this convention at the time of this writing.

Figure 2.2 shows a different representation of the intensity map on the newer, interactive maps on the USGS web site.

2.4 Ground Motion and Intensity Predictions

In areas distant from the control of seismic instrumentation or reported intensity, ground motions must be estimated using the available earthquake source parameters and GMPEs or Intensity Prediction Equations (IPEs). GMPEs are available for a wide range of magnitudes, source mechanisms, and tectonic settings. IPEs are still comparatively uncommon, with only a handful of published relations, focused on active tectonic and stable shield (cratonic) environments (e.g., *Atkinson and Wald, 2007*; *Allen et al., 2012*). To supplement the available IPEs, we have developed a "virtual IPE" which is a combination of the operator's selected GMPE and Ground Motion/Intensity Conversion Equation (GMICE), which work together to present the same interface and behaviors as a direct IPE, while being available for a wider range of regional and tectonic environments.

We describe the way ShakeMap employs ground-motion and intensity predictions in *ShakeMap Processing*. An up-to-date list of the GMPEs and IPEs available for ShakeMap can be found in the *Software Guide*.

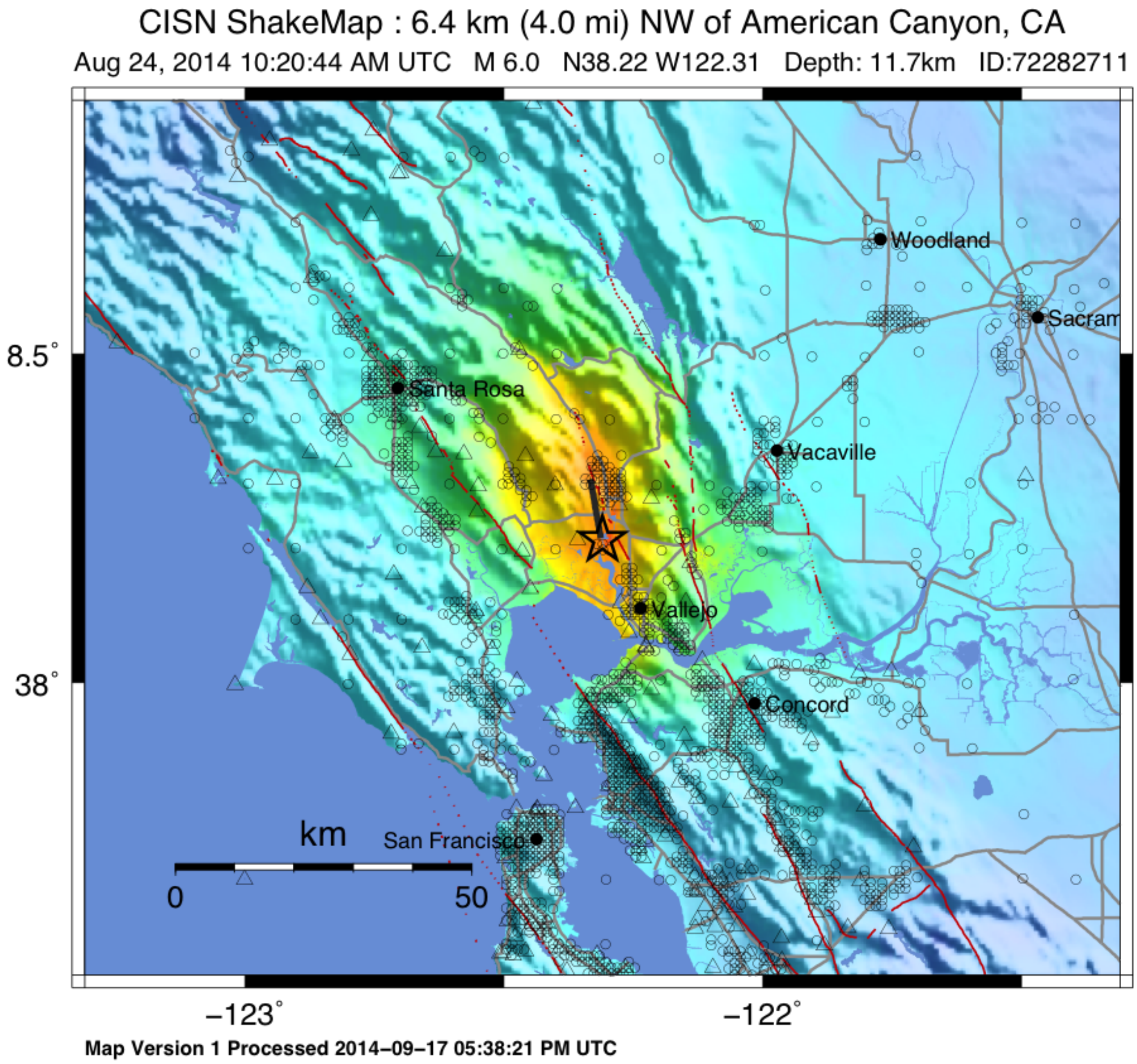
2.5 ShakeMap Processing

As discussed in the *User's Guide*, ShakeMap produces a range of output products. However, ShakeMap's primary outputs are grids of interpolated ground motions, from which the other grids, contours, and maps are derived. Interpolated grids are produced for PGA, PGV, macroseismic intensity (we will hereafter refer to macroseismic intensity as "MMI" for Modified Mercalli Intensity, but other intensity measures are supported), and (optionally) pseudo-spectral accelerations at 0.3, 1.0, and 3.0 sec. Attendant grids of shaking-parameter uncertainty and Vs30, are also produced as separate products or for later analyses of each intermediate processing step, if so desired.

The ShakeMap program responsible for producing the interpolated grids is called "*grind*". This section is a description of the way *grind* works, and some of the configuration parameters and command-line flags that control specific functionality. (For a complete description of configuring and running *grind*, see the *Software Guide* and the configuration file *grind.conf*.)

Below is an outline of the ShakeMap processing workflow. Figure 2.3 provides a schematic of the key processing steps.

1. Data Preparation
   (a) Remove flagged stations
   (b) Convert intensities to peak ground motions (PGMs) and vice versa
   (c) Correct data to "rock" using Vs30-based amplification terms



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<0.1*	*0.5*	*2.4*	*6.7*	*13*	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	*11*	*22*	*43*	*83*	*>160*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Fig. 2.1: Intensity ShakeMap from the 2014 M6.0 American Canyon (Napa Valley), CA earthquake. Strong motion data (triangles) and intensity data (circles) are color-coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Wald et al. (1999b)* as shown in the legend. The north-south black line indicates the fault location, which nucleated near the epicenter (red star). Note: Map Version Number reflects separate offline processing for this Manual.

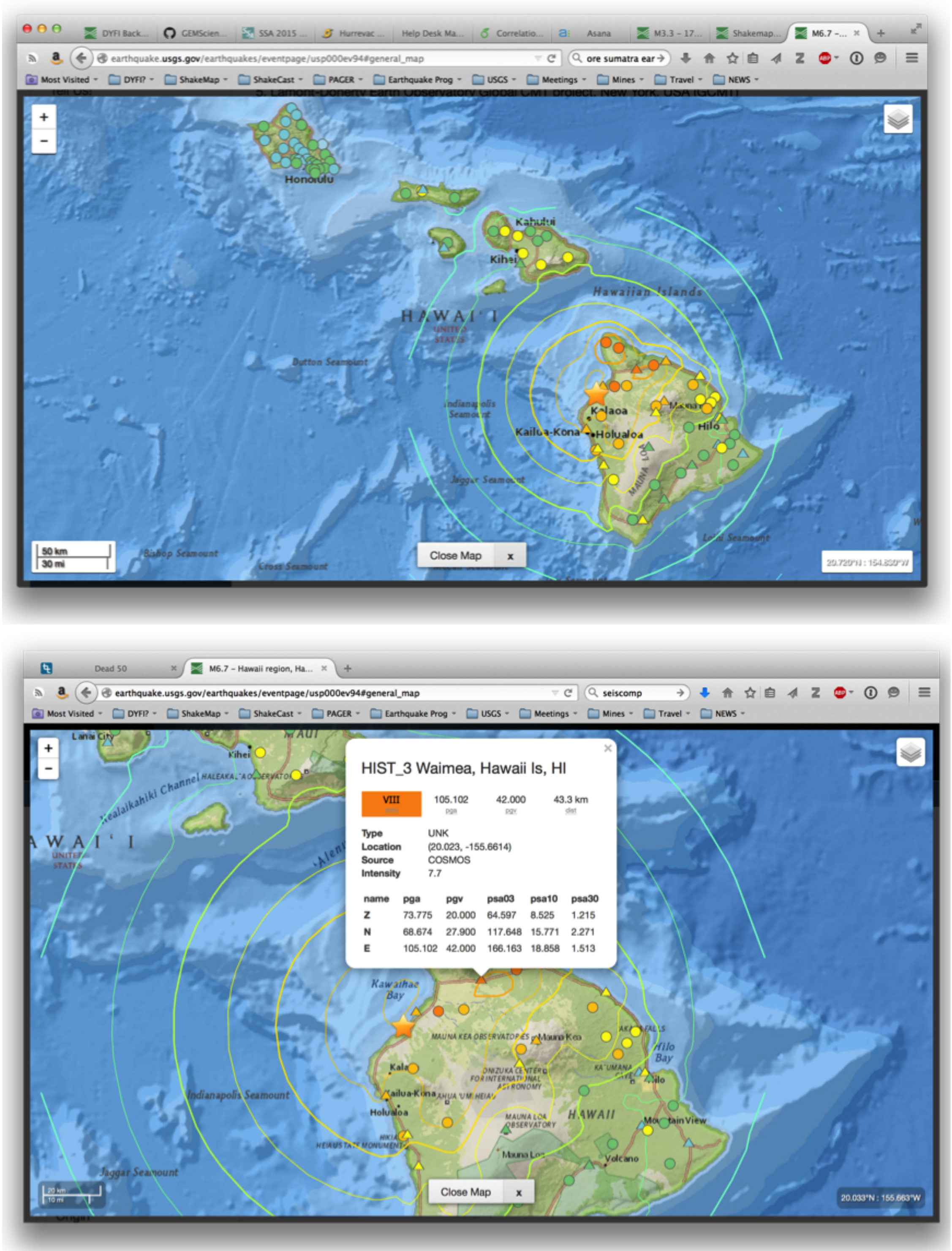


Fig. 2.2: Intensity ShakeMap from the 2006 M6.7 Kahola Bay, HI earthquake. Contours indicate intensities; strong motion data (triangles) and intensity data (circles) are color- coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Worden et al. (2012)*. Inset on lower map shows pop-up station information.

   (d) Remove estimated basin response (optional)

2. Correct earthquake bias with respect to the chosen GMPE

   (a) Remove the effect of directivity (optional)

   (b) Compute bias

   (c) Flag outliers

   (d) Repeat the previous two steps until no outliers are found

   (e) Create bias-adjusted GMPE estimates at each station location and for the entire output grid (optionally, apply directivity)

3. Interpolate ground motions to a uniform grid

4. Amplify ground motions

   (a) Basin amplifications (optional)

   (b) Vs30 site amplifications

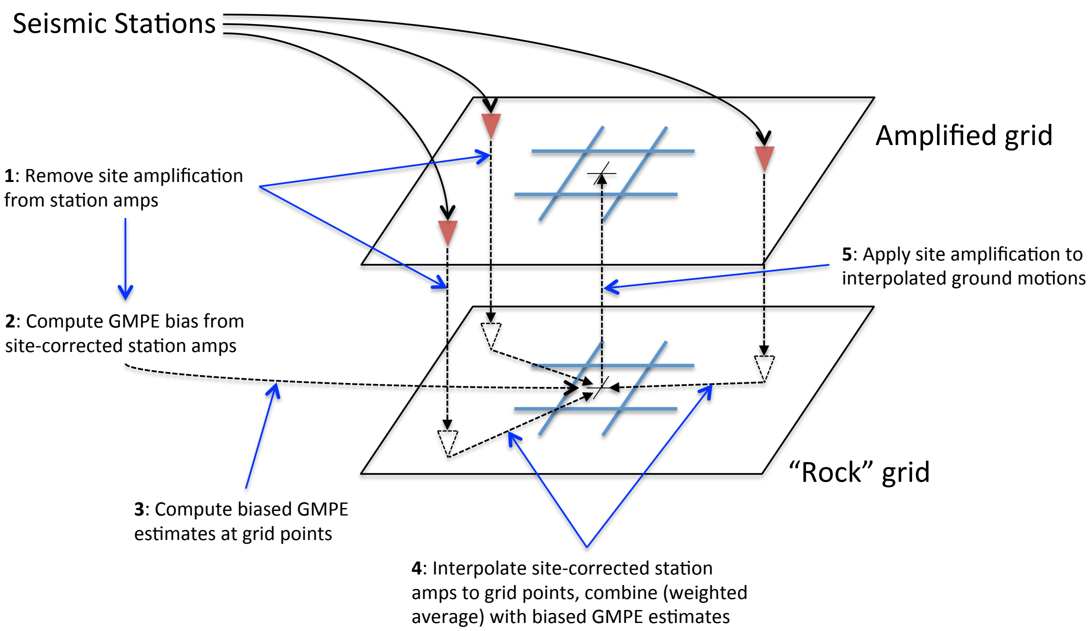


Fig. 2.3: A schematic of the basic ShakeMap ground motion interpolation scheme.

The sections that follow provide a more complete description of the processing steps outlined above.

2.5.1 Data preparation

The first step in processing is the preparation of the parametric data. As discussed in the *Software Guide*, ground motion amplitudes are provided to ShakeMap in the form of Extended Markup Language (XML) files. Note that we describe here the behavior of *grind* with respect to the input XML file(s). The programs that produce the input XML (be it *db2xml*, others, or the network operator's custom codes) will have their own rules as to what is included in the input.

In our presentation here, the term "station" refers to a single seismographic station denoted with a station ID (i.e., a code or number). In current practice, station IDs often consist of a network identifier concatenated (using a ".") with the station ID (e.g., "CI.JVC" or "CE.50281").

Each station may have one or more "channels," each of which is denoted by an ID code (often called a "seedchan"). The last character of the ID is assumed to be the orientation of the instrument (east-west, north-south, vertical). ShakeMap only uses the peak horizontal component. Thus, ShakeMap does not consider amplitudes with a "Z" as the final character, though it does carry the vertical amplitude values through to the output station files. Note that some stations in some networks are given orientations of "1", "2", and "3" (rather than the more standard "N", "E", and "Z"), where any of the components may be vertical. Because of the non-standardized nature of these component labels, ShakeMap does not attempt to discern their orientation and assumes that they are all horizontal. This can lead to inaccuracies—it becomes the network operator's responsibility to ensure that the vertical channel is either excluded or labeled with a "Z" before the data are presented to ShakeMap. Similarly, many networks co-locate broadband instruments with strong-motion instruments and produce PGMs for both. Again, it is the network operator's responsibility to select the instrument that best represents the data for the PGMs in question. Aside from the station flagging discussed below, ShakeMap makes no attempt to discern which of a set of components is superior, it will simply use the largest value it finds (i.e., if ShakeMap sees channels "HNE" and "HHE" for the same station, it will simply use the larger of the two PGMS without regard to the possibility that one may be off-scale or below-noise).

Currently, ShakeMap is location-code agnostic. Because the current SNCL (Station, Network, Channel, Location) specification defines the location code as a pure identifier (i.e., it should have no meaning), it is impossible to anticipate all the ways it may be used. Therefore, if a network-station combo has multiple instruments at multiple locations, the data provider should identify each location as a distinct station for ShakeMap XML input purposes (by, for example, including the location code as part of the station identifier, N.S.L—e.g., 'CI.JVC.01'). If the network uses the location codes in another manner, it is up to the operator to generate a station/component data structure that ShakeMap will handle correctly.

Finally, each channel may produce one or more amplitudes (e.g., PGA, PGV, pseudo- spectral acceleration). Note that these amplitudes should always be supplied by the network as positive values, regardless of the direction of the peak motion. The amplitudes for all stations and channels are collected and reported, but only the peak horizontal amplitude of each ground-motion parameter is used by ShakeMap.

The foregoing is not intended to be a complete description of the requirements for the input data. Please see the relevant section of the *Software Guide* for complete information.

Flagged Stations

If the "flag" attribute of any amplitude in the input XML is non-null and non-zero, then all components of that station are flagged as unusable. The reasoning here is that for a given data stream, the typical network errors (telemetry glitch, incomplete data, off-scale or below-noise data, etc.) will affect all of the parameters (as they are typically all derived from the same data stream), and it is therefore impossible to determine the peak horizontal component of any ground-motion parameter. This restriction is not without its detractors, however, and we may revisit it at a future date.

MMI data are treated in much the same way; however, there is typically only one "channel" and one parameter (i.e., intensity).

ShakeMap presents flagged stations as open, unfilled triangles on maps and on regression plots. In contrast, unflagged stations are color coded by network or, optionally, by their amplitudes via their converted intensity value, as shown in

Figure 2.4. Flagged stations are also indicated as such within tables produced for ShakeMap webpage consumption, e.g., the *stations.xml* file.

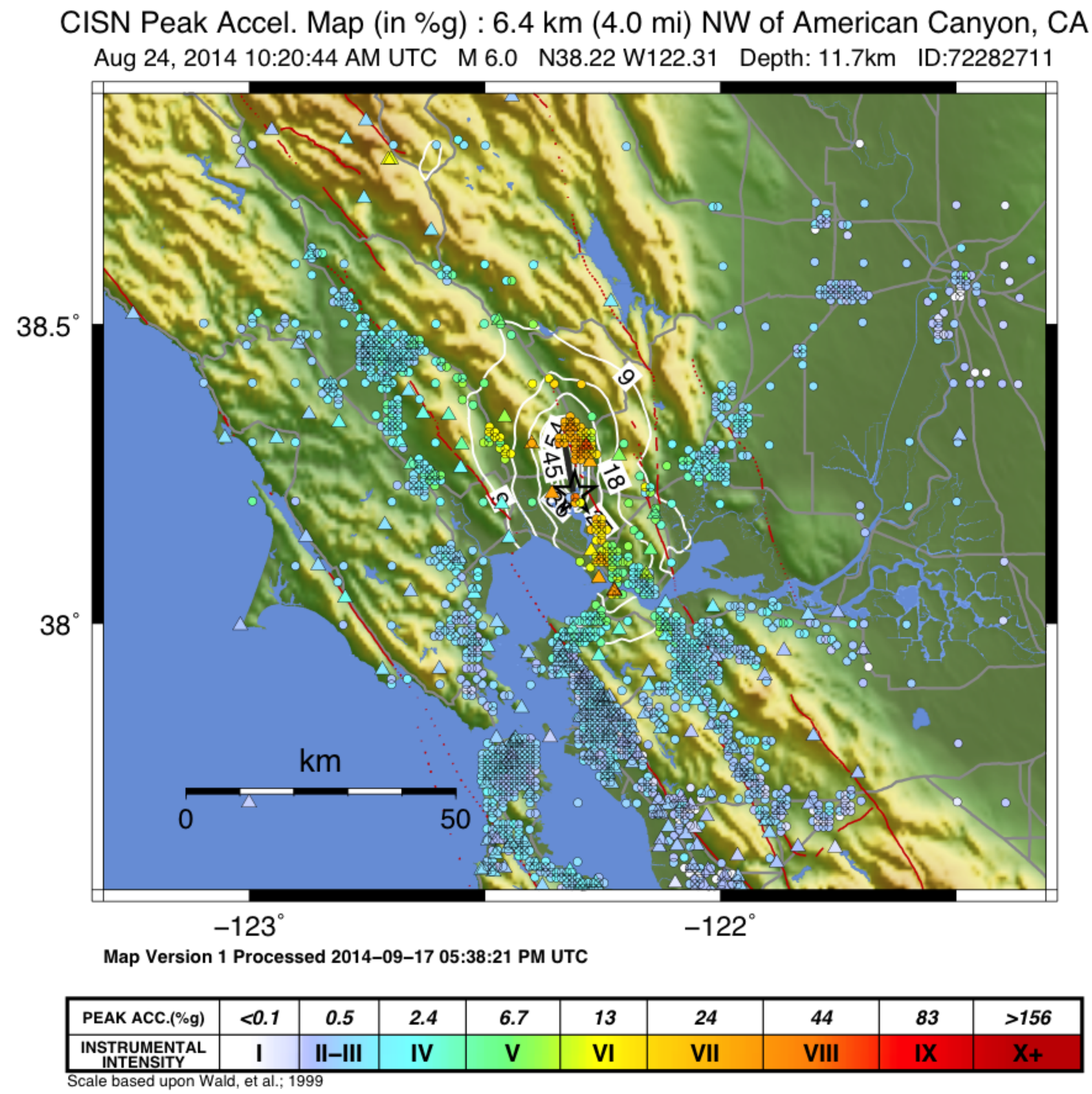


Fig. 2.4: Peak acceleration ShakeMap from the Aug. 24, 2014, M6.0 American Canyon (Napa Valley), California earthquake. Strong motion data (triangles) and intensity data (circles) are color-coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Wald et al. (1999b)* as shown in the legend. The north-south black line indicates the fault location, which nucleated near the epicenter (red star). Note: Map Version Number reflects separate offline processing for this Manual.

Converting MMI to PGM and PGM to MMI

Once the input data have been read and peak amplitudes assigned for each station (which may be null if the data are flagged), intensities are derived from the peak amplitudes and peak amplitudes are derived from the intensities using the GMICEs configured (see the parameters 'pgm2mi' and 'mi2pgm' in *grind.conf*). Small values of observed intensities (MMI < III for PGA, and MMI < IV for other parameters) are not converted to PGM for inclusion in the

PGM maps. Our testing indicated that including these low intensities introduced a significant source of error in the interpolation, likely due to the very wide range (and overlap) of ground motions that can produce MMIs lower than III or IV.

Site Corrections

Near-surface conditions can have a substantial effect on ground motions. Ground motions at soft-soil sites, for instance, will typically be amplified relative to sites on bedrock. Because we wish to interpolate sparse data to a grid over which site characteristics may vary greatly, we first remove the effects of near-surface amplification from our data, perform the interpolation to a uniform grid at bedrock conditions, and then apply the site amplifications to each point in the grid, based on each site's characteristics.

A commonly used proxy used to account for site effects (e.g., *Borcherdt, 1994*) is Vs30, the time-averaged shear wave velocity to 30 meters depth. Vs30 is also a fundamental explanatory variable for modern GMPEs (e.g., *Abrahamson et al., 2014*). Since the use of GMPEs for ground motion estimation is fundamental to ShakeMap, we follow this convention and use Vs30-based amplification terms to account for site amplification. In *Future Directions*, we suggest alternative approaches that require additional site information beyond Vs30.

Site Characterization Map

Each region wishing to implement ShakeMap should have a Vs30 map that covers the entire area they wish to map. Using the Jan. 17, 1994, M6.7 Northridge, California earthquake ShakeMap as an example (Figure 2.5), we present, in Figure 2.6, the Vs30 map used. Until 2015, the California site-condition map was based on geologic base maps as introduced by *Wills et al. (2000)*, and modified by Howard Bundock and Linda Seekins of the USGS at Menlo Park (H. Bundock, written comm., 2002). The Wills et al. map extent is that of the State boundary; however, ShakeMap requires a rectangular grid, so fixed velocity regions were inserted to fill the grid areas representing the ocean and land outside of California. Unique values were chosen to make it easy to replace those values in the future. The southern boundary of the Wills et al. map coincides with the U.S.A./Mexico border. However, due to the abundant seismic activity in Imperial Valley and northern Mexico, we have continued the trend of the Imperial Valley and Peninsular Ranges south of the border by approximating the geology based on the topography; classification BC was assigned to sites above 100m in elevation and CD was assigned to those below 100m. This results in continuity of our site correction across the international border.

Other ShakeMap operators have employed existing geotechnically- or geologically-based Vs30 maps, or have developed their own Vs30 map for the area covered by their ShakeMap. For regions lacking such maps, including most of globe, operators often employ the approach of *Wald and Allen (2007)*, revised by *Allen and Wald, (2009b)*, which provides estimates of Vs30 as a function of more readily available topographic slope data. Wald and Allen's slope-based Vs30-mapping proxy is employed by the Global ShakeMap (GSM) system.

Recent developments by *Wald et al. (2011d)* and *Thompson et al. (2012*; *2014*) provide a basis for refining Vs30 maps when Vs30 data constraints are abundant. Their method employs not only geologic units and topographic slope, but also explicitly constrains map values near Vs30 observations using kriging-with-a-trend to introduce the level of spatial variations seen in the Vs30 data (*Thompson et al., 2014*). An example of Vs30 for California using this approach is provided in Figure 2.7. Thompson et al. describe how differences among Vs30 base maps translate into variations in site amplification in ShakeMap.

Worden et al. (2015) further consolidate readily available Vs30 map grids used for ShakeMaps at regional seismic networks of the ANSS with background, Thompson et al.'s California Vs30 map, and the topographic-based Vs30 proxy to develop a consistently scaled mosaic of Vs30 maps for the globe with smooth transitions from tile to tile. It is anticipated that aggregated Vs30 data provided by *Yong et al. (2015)* will facilitate further map development of other portions of the U.S.

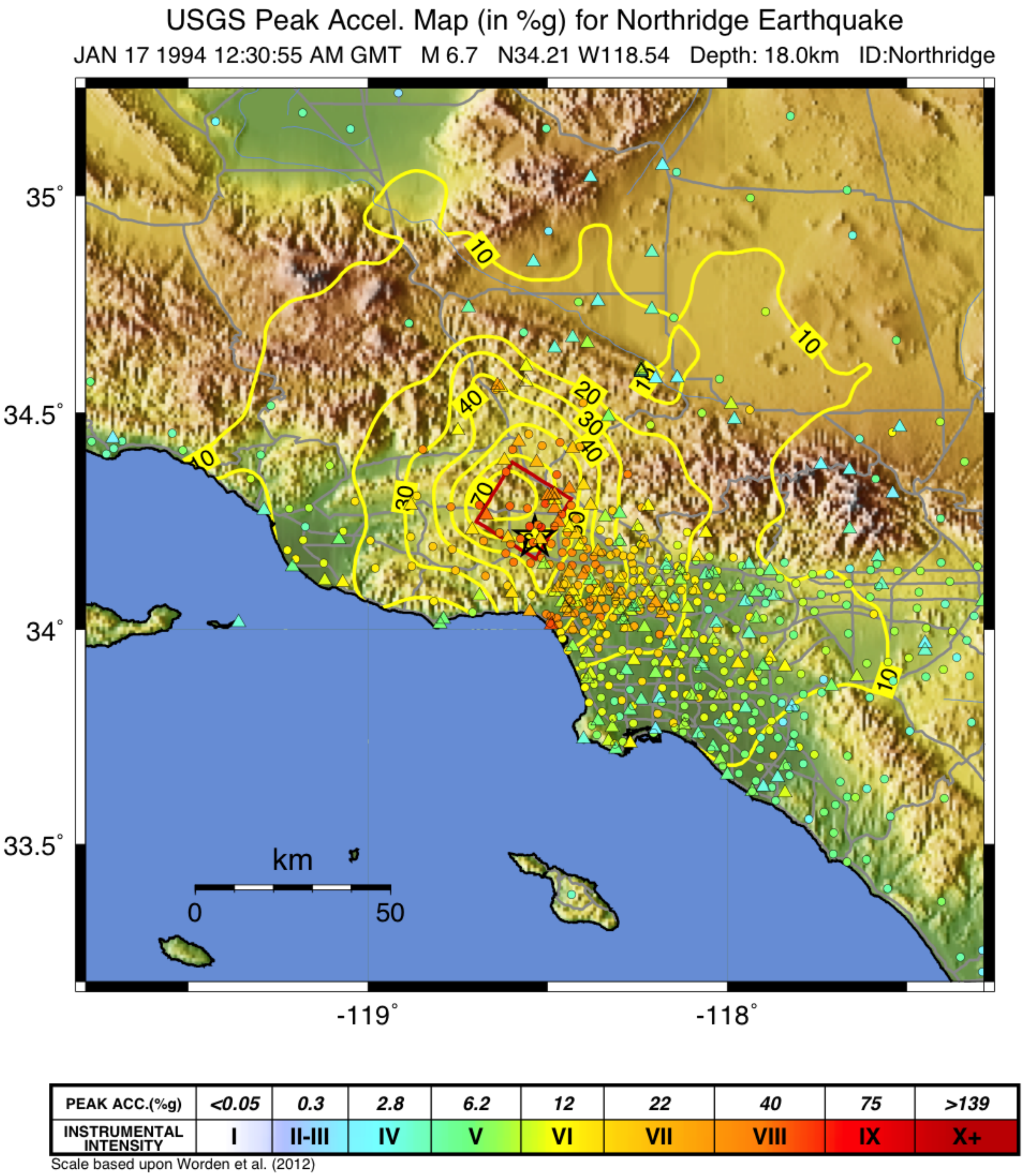


Fig. 2.5: PGA ShakeMap reprocessed with data from the 1994 M6.7 Northridge, CA earthquake with a finite fault (red rectangle), strong motion data (triangles), and intensity data (circles). Stations and macroseismic data are color-coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Worden et al. (2012)* and indicated by the scale shown.

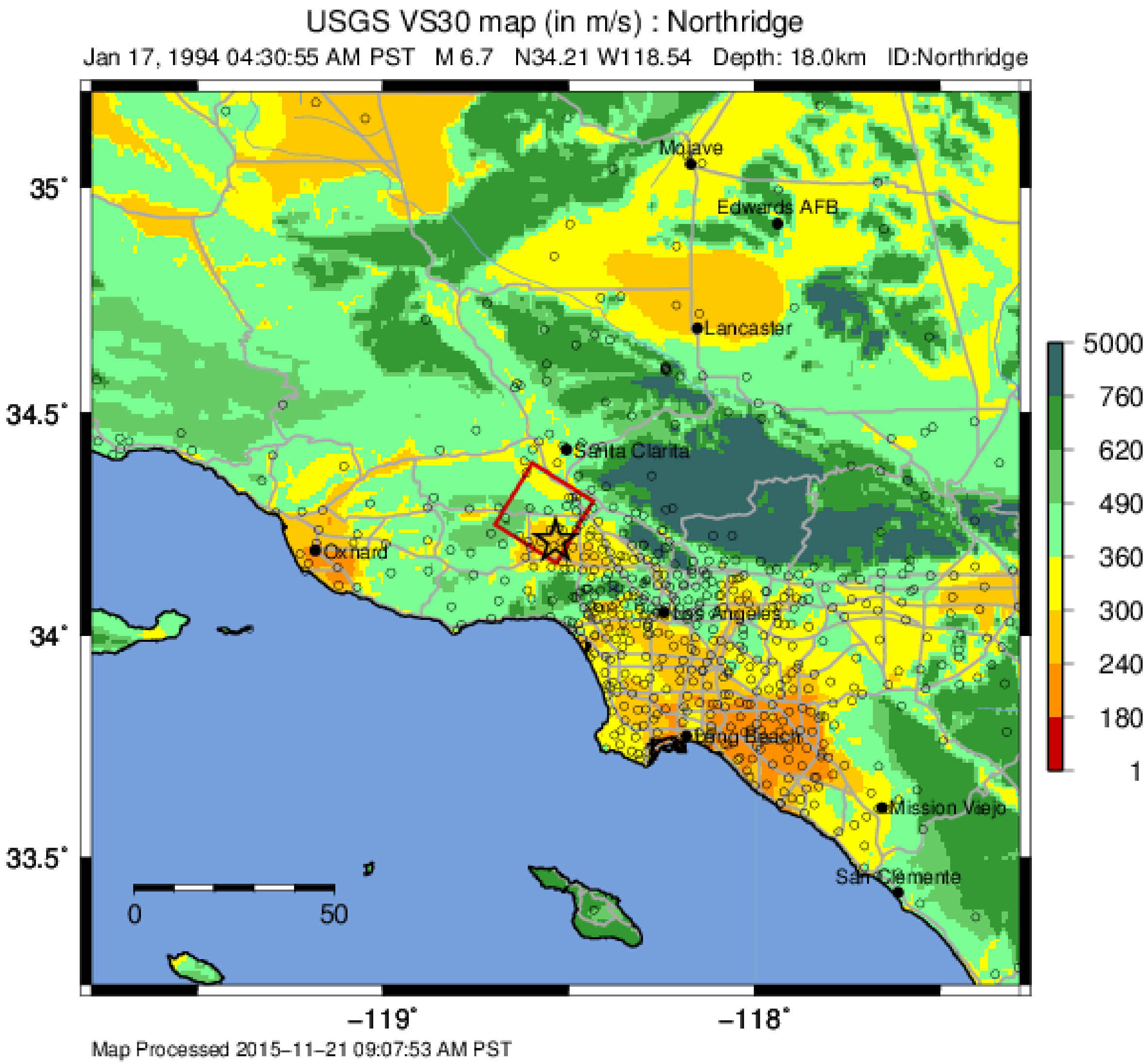


Fig. 2.6: Vs30 Map produced as a byproduct of ShakeMap for the 1994 M6.7 Northridge, CA earthquake. The finite fault is shown as a red rectangle; strong motion data (triangles) and intensity data (circles) are transparent to see site conditions. The legend indicates the range of color-coded Vs30 values in m/sec.

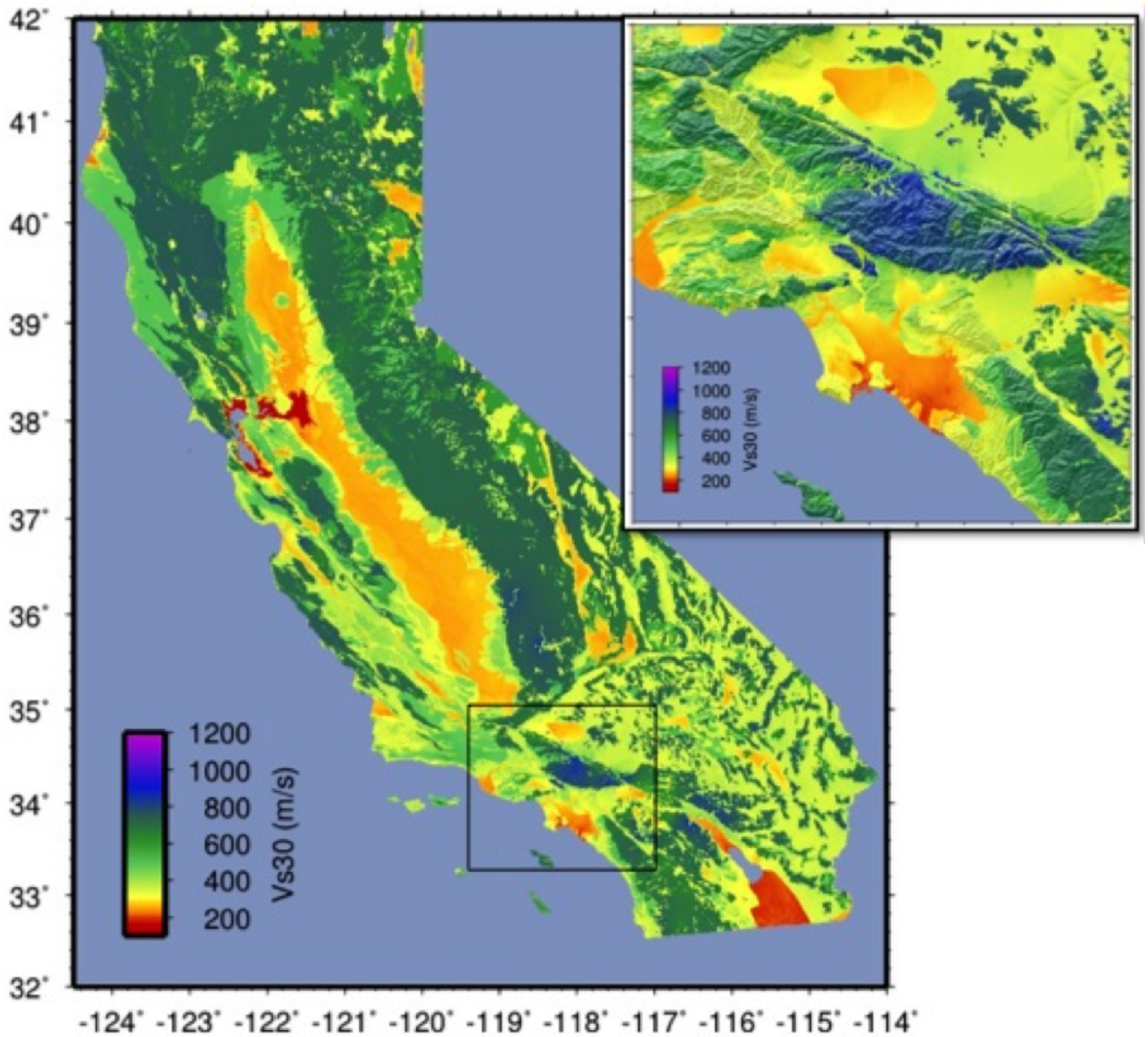


Fig. 2.7: Revised California Vs30 Map (*Thompson et al., 2014*). This map combines geology, topographic slope, and constraints of map values near Vs30 observations using kriging-with-a-trend. Inset shows Los Angeles region, with Los Angeles Basin indicating low Vs30 velocities.

Amplification Factors

ShakeMap provides two operator-selectable methods for determining the factors used to amplify and de-amplify ground motions based on Vs30. The first is to apply the frequency- and amplitude-dependent factors, such as those determined by *Borcherdt (1994)* or *Seyhan and Stewart (2014)*. By default, amplification of PGA employs Borcherdt's short-period factors; PGV uses mid-period factors; and PSA at 0.3, 1.0, and 3.0 sec uses the short-, mid-, and long-period factors, respectively. The second method uses the site correction terms supplied with the user's chosen GMPE (if such terms are supplied for that GMPE). The differences between these choices and their behavior with respect to other user-configurable parameters are discussed in the *Software & Implementation Guide*.

Correct Data to "Rock"

If, as is usually the case, the operator has opted to apply site amplification (via the *-qtm* option to *grind*), the ground-motion observations are corrected (de-amplified) to "rock". (The Vs30 of "rock" is specified with the parameter 'smVs30default' in *grind.conf*.) See the section "Site Corrections" in the *Software Guide* for a complete discussion of the way site amplifications are handled and the options for doing so.

Note that Borcherdt-style corrections do not handle PGV directly, so PGV is converted to 1.0 sec PSA (using *Newmark and Hall, 1982)*, (de)amplified using the mid-period Borcherdt terms, and then converted back to PGV. The Newmark and Hall conversion is entirely linear and reversible, so while the conversion itself is an approximation, no bias or uncertainty remains from the conversion following a "round trip" from site to bedrock back to site.

Because there are no well-established site correction terms for MMI, when Borcherdt- style corrections are specified, ShakeMap converts MMI to PGM, applies the (de)amplification to PGM using the Borcherdt terms, then converts the PGMs back to MMI.

Figure 2.8 and Figure 2.9 show shaking estimates (for PGA and MMI, respectively) before site correction (upper left) and after (upper right). Without site correction, ground motion attenuation is uniform as a function of hypocentral distance (in the absence of a finite fault model as in panels A through C) and fault distance (as in D); with site correction, the correlation of amplitudes with the Vs30 map (and also topography) are more apparent. This distinction is important: often complexity in ShakeMap's peak ground motions and intensity patterns are driven by site terms, rather than variability due to shaking observations.

As the final step in correcting the observations to "rock," if basin amplification is specified (with the *-basement* flag), the basin amplifications are removed from the PGM data. Currently, basin amplifications are not applied to MMI.

2.5.2 Event Bias

ShakeMap uses ground motion prediction equations (GMPEs) and, optionally, intensity prediction equations (IPEs) to supplement sparse data in its interpolation and estimation of ground motions. If sufficient data are available, we compute an event bias that effectively removes the inter-event uncertainty from the selected GMPE (IPE). This approach has been shown to greatly improve the quality of the ShakeMap ground motion estimates (for details, see *Worden et al., 2012*).

The bias-correction procedure is relatively straightforward: the magnitude of the earthquake is adjusted so as to minimize the misfit between the observational data and estimates at the observation points produced by the GMPE. If the user has chosen to use the directivity correction (with the *-directivity* flag), directivity is applied to the estimates.

In computing the total misfit, primary observations (i.e., ground-motion observations from seismic stations or MMI observations from *Did You Feel It?* or field surveys) are weighted as if they were GMPE predictions, whereas converted observations (i.e., primary obsertations of one type converted to another type, such as ground-motion observations converted to MMI) are down-weighted by treating them as if they were GMPE predictions converted using the GMICE (i.e., primary observations are given full weighting, whereas the converted observations are given a substantially lower weight.) Once a bias has been obtained, we flag (as outliers) any data that exceed a user- specified threshold (often three times the sigma of the GMPE at the obsertation point). The bias is then recalculated and the flagging is repeated

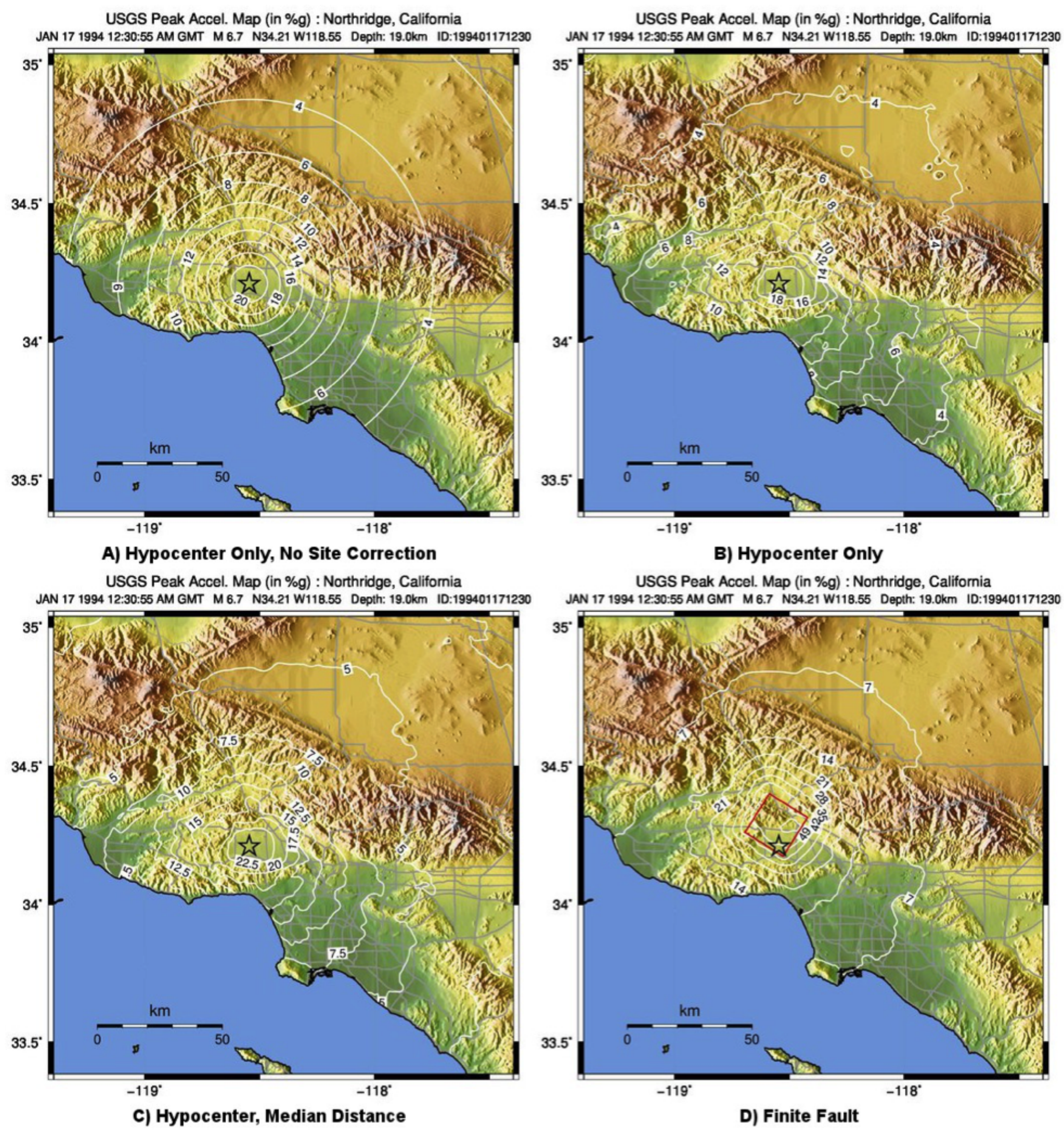


Fig. 2.8: ShakeMap peak ground acceleration maps for the 1994 M6.7 Northridge, CA earthquake without strong motion or intensity data. A) Hypocenter only, without site amplification; B) Hypocenter, site amplification added; C) Hypocenter only, but with median distance correction added; and D) Finite fault (red rectangle) added.

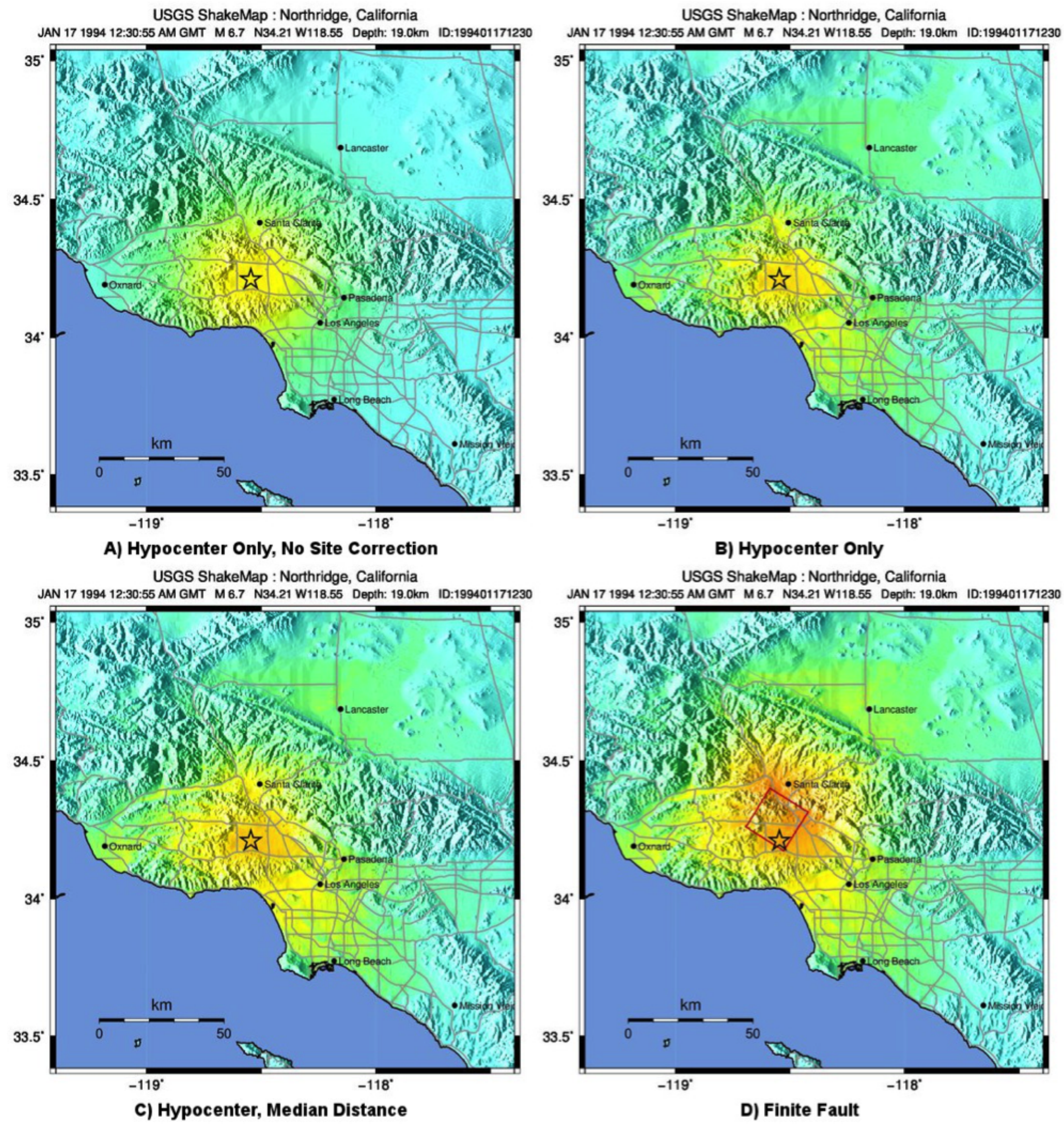


Fig. 2.9: ShakeMap intensity maps for the 1994 M6.7 Northridge, CA earthquake without strong motion or intensity data. A) Hypocenter only, without site amplification; B) Hypocenter, site amplification added; C) Hypocenter only, but with median distance correction added; and D) Finite fault (red rectangle) added.

until no outliers are found. The flagged outliers are then excluded from further processing (though the operator can choose to modify the outlier criteria or impose their inclusion).

(There are a number of configuration parameters that affect the bias computation and the flagging of outliers—see the *Software Guide* and *grind.conf* for a complete discussion of these parameters.)

The bias-adjusted GMPE is then used to create estimates for the entire output grid. If the user has opted to include directivity effects, they are applied to these estimates. See the *Interpolation* section for the way the GMPE-based estimates are used.

The Northridge earthquake ShakeMap provides an excellent example of the effect of bias correction. Overall, the ground motions for the Northridge earthquake exceed average estimates of existing GMPEs—in other words, it has a significant positive inter-event bias term (see Figure 2.10 and Figure 2.11, which show PGA and PGV, respectively).

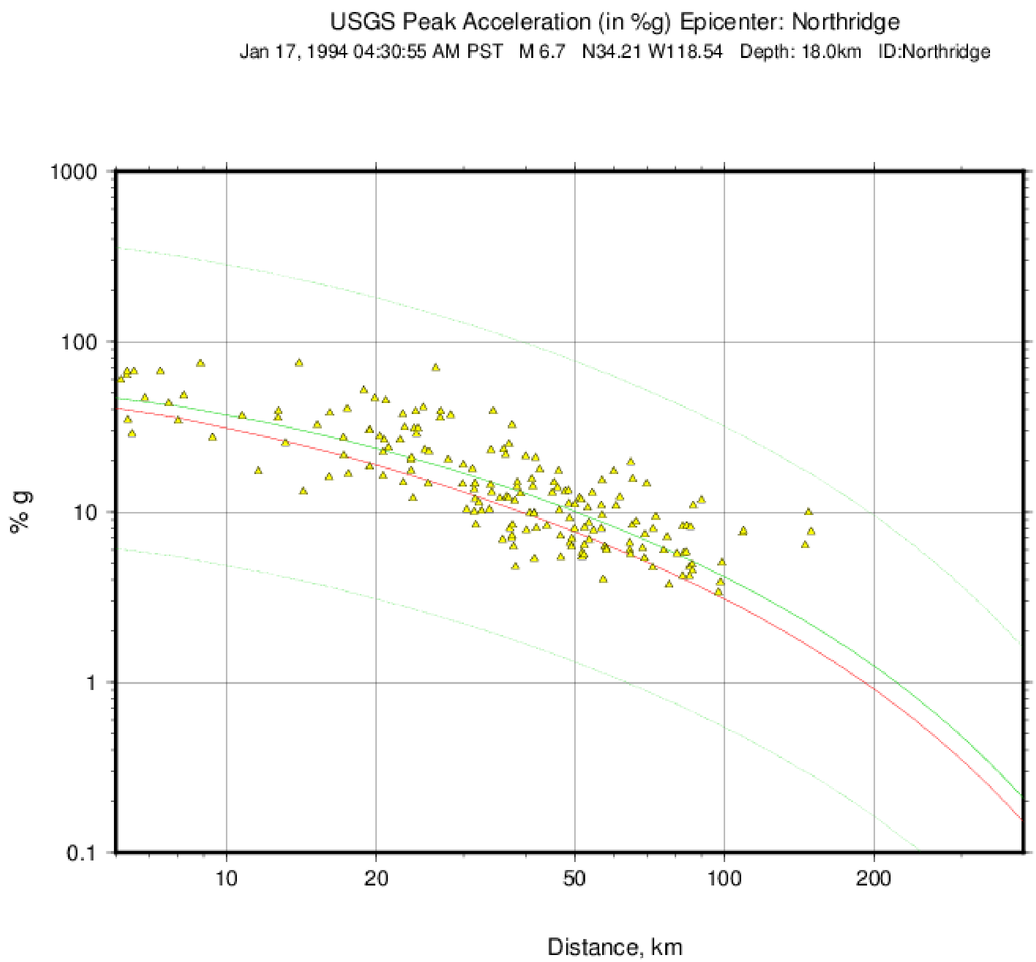


Fig. 2.10: Plot of Northridge earthquake PGAs as a function of distance. The triangles show recorded ground motions; the red line shows the unbiased *Boore and Atkinson (2008)* (BA08) GMPE; the dark green lines show BA08 following the bias correction described in the text; the faint green lines show the bias-adjusted GMPE +/- three standard deviations.

The ShakeMap bias correction accommodates this behavior once a sufficient number of PGMs or intensity data are added (e.g., Figure 2.12 and Figure 2.13 A and C, show before and after bias correction, respectively). The addition of the stations provides direct shaking constraints at those locations; the bias correction additionally affects the map wherever ground motion estimates dominate (i.e., away from the stations).

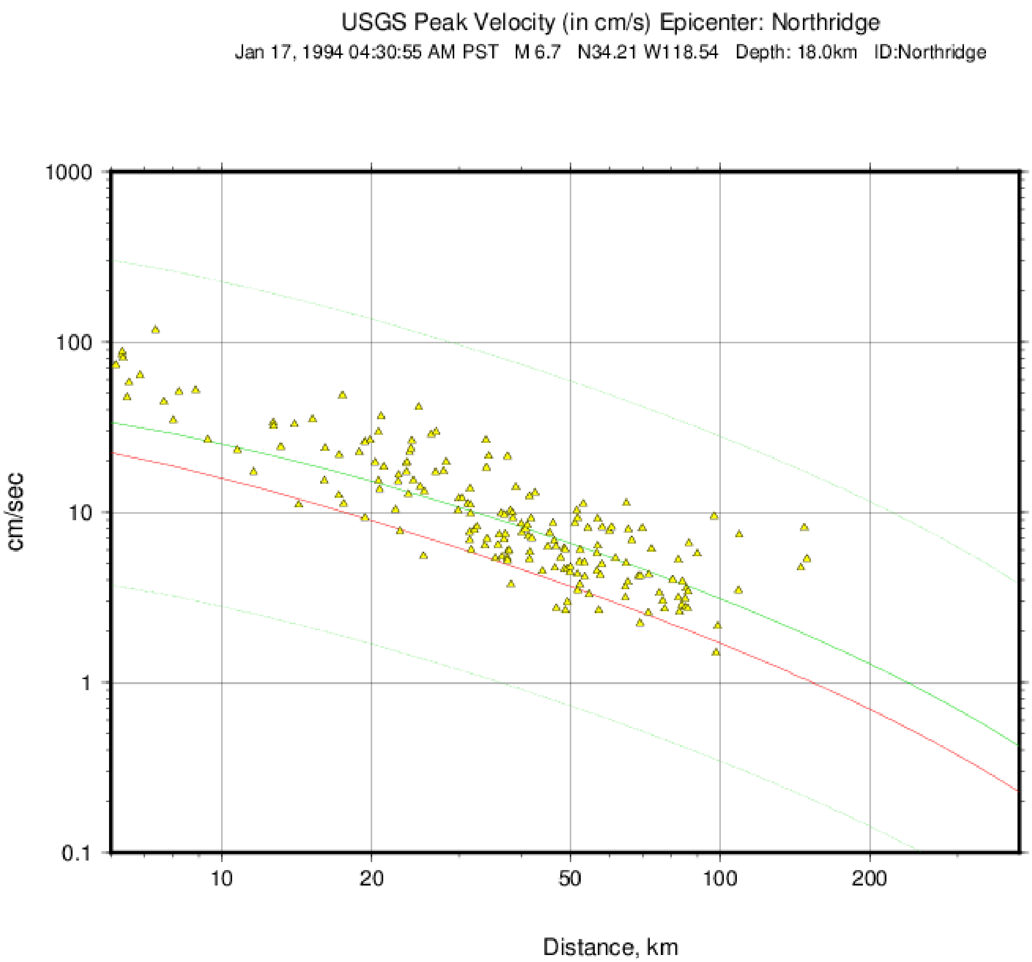


Fig. 2.11: Plot of Northridge earthquake PGVs as a function of distance. The triangles show recorded ground motions; the red line shows the unbiased *Boore and Atkinson (2008)* (BA08) GMPE; the dark green lines show BA08 following the bias correction described in the text; the faint green lines show the bias-adjusted GMPE +/- three standard deviations.

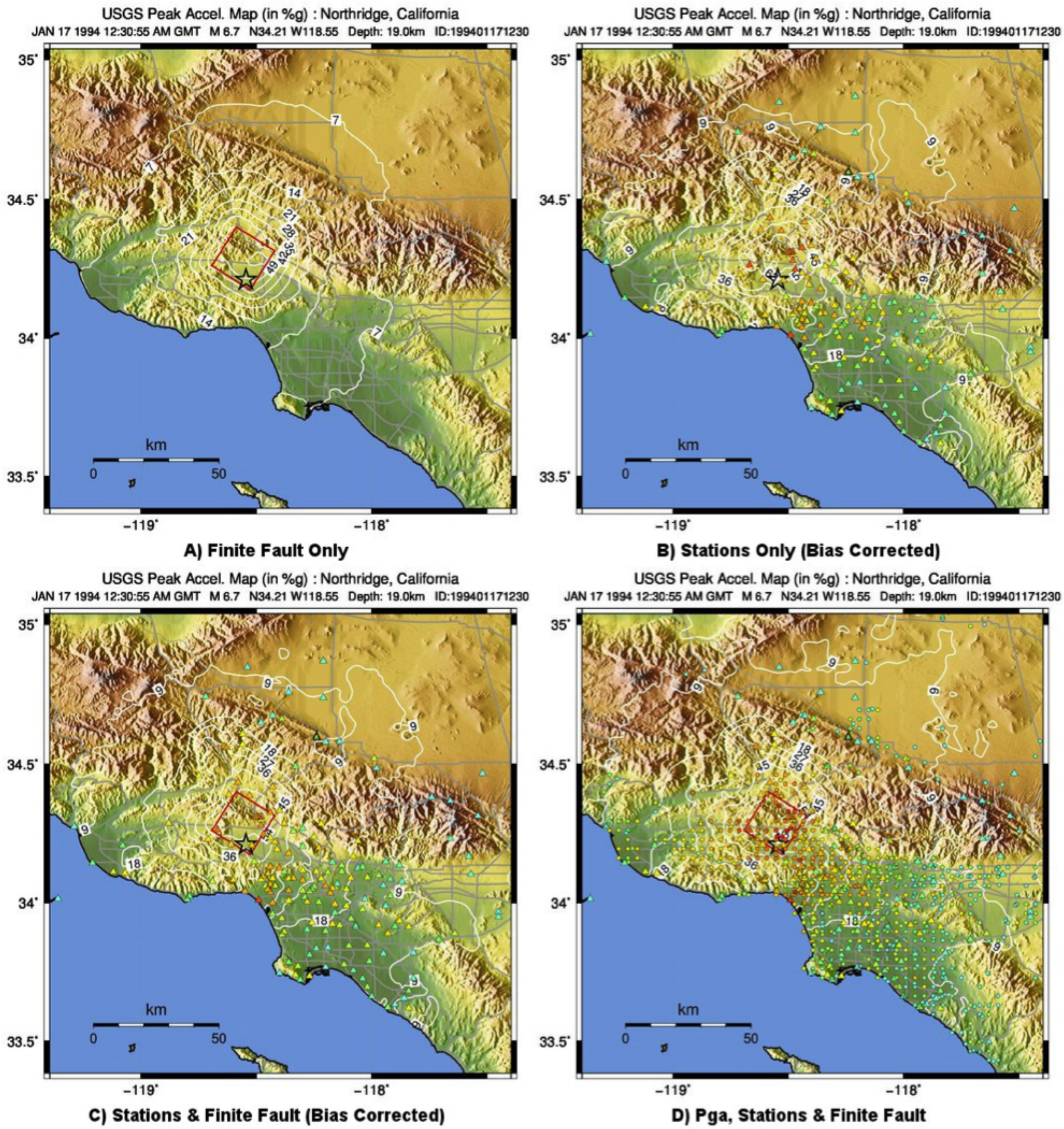


Fig. 2.12: PGA ShakeMaps for the Northridge earthquake, showing effects of adding strong motion and intensity data. A) Finite fault only (red rectangle), no data; B) Strong motion stations (triangles) only; C) Finite Fault and strong motion stations (triangles); D) Finite Fault strong motion stations (triangles) and macroseismic data (circles). Notes: Stations and macroseismic observations are color-coded to their equivalent intensity using *Worden et al. (2012)*.

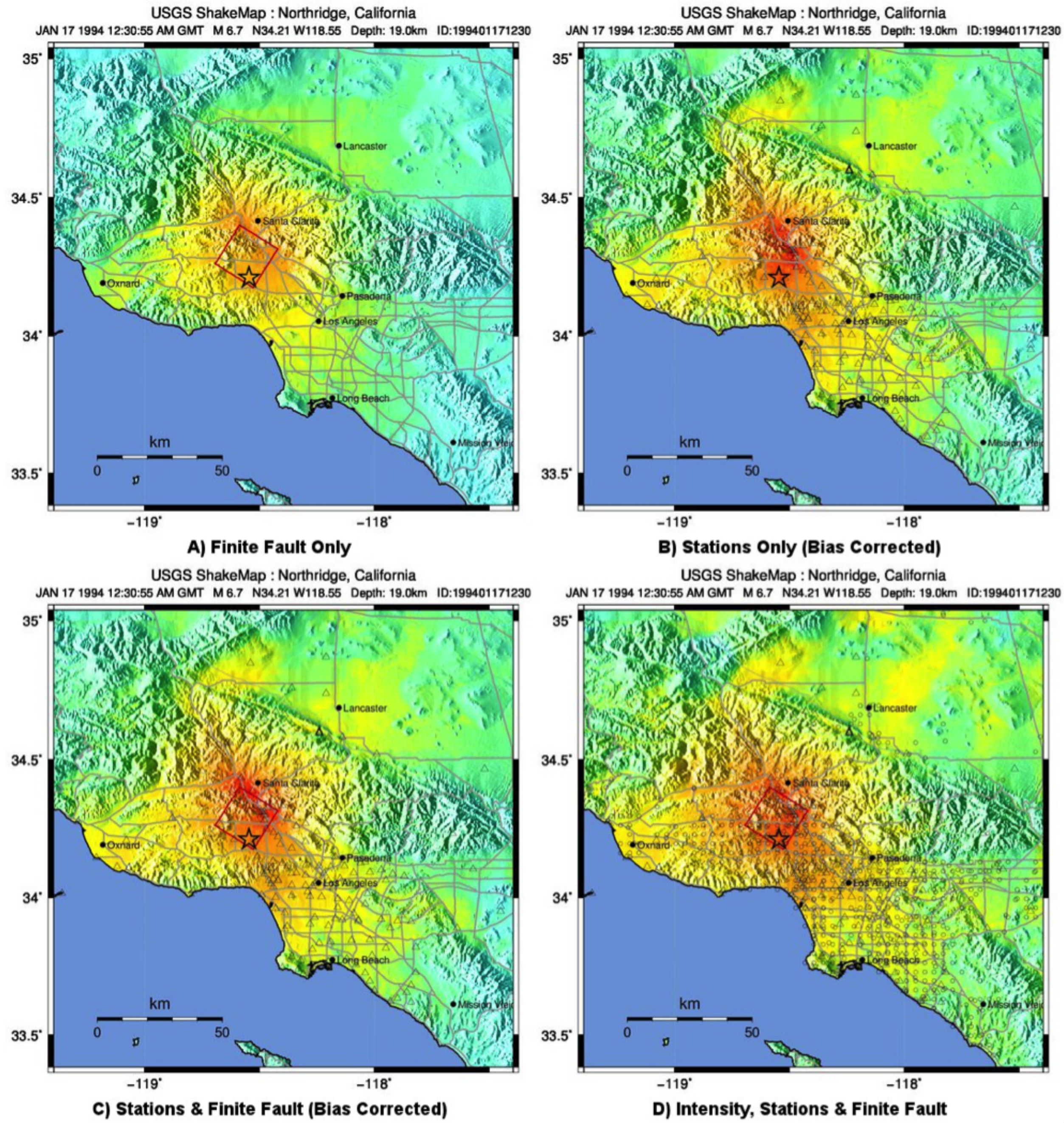


Fig. 2.13: Intensity ShakeMaps for the Northridge earthquake, showing effects of adding strong motion and intensity data. A) Finite fault only (red rectangle), no data; B) Strong motion stations (triangles) only; C) Finite Fault and strong motion stations (triangles); D) Finite Fault strong motion stations (triangles) and macroseismic data (circles). Notes: (D) is the best possible constrained representation for this earthquake. The finite fault model without data (A) is not bias-corrected; for the Northridge earthquake, the inter-event biases are positive, indicating higher than average ground shaking for M6.7; thus, the unbiased map (A) tends to under-predict shaking shown in the data-rich, best-constrained map (D).

2.5.3 Interpolation

The interpolation procedure is described in detail in *Worden et al. (2010)*. Here we summarize it only briefly.

To compute an estimate of ground motion at a given point in the latitude-longitude grid, ShakeMap finds an uncertainty-weighted average of 1) direct observations of ground motion or intensity, 2) direct observations of one type converted to another type (i.e., PGM converted to MMI, or vice versa), and 3) estimates from a GMPE or IPE. Note that because the output grid points are some distance from the observations, we use a spatial correlation function to obtain an uncertainty for each observation when evaluated at the outpoint point. The total uncertainty at each point is a function of the uncertainty of the direct observations obtained with the distance-to-observation uncertainty derived from the spatial correlation function, and that of the GMPE or IPE.

In the case of direct ground-motion observations, the uncertainty at the observation site is assumed to be zero, whereas at the "site" of a direct intensity observation, it is assumed to have a non-zero uncertainty due to the spatially averaged nature of intensity assignments. The uncertainty for estimates from GMPEs (and IPEs) is the stated uncertainty given in the generative publication or document. The GMPE uncertainty is often spatially constant, but this is not always the case, especially with more recent GMPEs.

For converted observations, a third uncertainty is combined with zero-distance uncertainty and the uncertainty due to spatial separation: the uncertainty associated with the conversion itself (i.e., the uncertainty of the GMICE). This additional uncertainty results in the converted observations being down-weighted in the average, relative to the primary observations.

Because a point in the output may be closer to or farther from the source than a nearby contributing observation, the observation is scaled by the ratio of the GMPE (or IPE) estimates at the output point and the observation point:

$$Y_{obs,xy} = Y_{obs} \times \left(\frac{Y_{\text{GMPE},xy}}{Y_{\text{GMPE},obs}} \right), \tag{2.1}$$

where Y_{obs} is the observation, and $Y_{\text{GMPE},obs}$ and $Y_{\text{GMPE},xy}$ are the ground-motion predictions at the observation point and the point (*x*,*y*), respectively. This scaling is also applied to the converted observations with the obvious substitutions. Note that the application of this term also accounts for any geometric terms (such as directivity or source geometry) that the ground-motion estimates may include.

The formula for the estimated ground motion at a point (*x*,*y*) is then given by:

$$\overline{Y_{xy}} = \frac{\dfrac{Y_{\text{GMPE},xy}}{\sigma^2_{\text{GMPE}}} + \sum_{i=1}^{n} \dfrac{Y_{obs,xy,i}}{\sigma^2_{obs,xy,i}} + \sum_{j=1}^{n} \dfrac{Y_{conv,xy,j}}{\sigma^2_{conv,xy,j}}}{\dfrac{1}{\sigma^2_{\text{GMPE}}} + \sum_{i=1}^{n} \dfrac{1}{\sigma^2_{obs,xy,i}} + \sum_{j=1}^{n} \dfrac{1}{\sigma^2_{conv,xy,j}}}, \tag{2.2}$$

where $Y_{\text{GMPE},xy}$ and σ^2_{GMPE} are the amplitude and variance, respectively, at the point (*x*,*y*) as given by the GMPE, $Y_{obs,xy,i}$ are the observed amplitudes scaled to the point (*x*,*y*), $\sigma^2_{obs,xy,i}$ is the variance associated with observation *i* at the point (*x*,*y*), $Y_{conv,xy,j}$ are the converted amplitudes scaled to the point (*x*,*y*), and $\sigma^2_{conv,xy,j}$ is the variance associated with converted observation *j* at the point (*x*,*y*).

We can then compute the estimated IM (Equation (2.2)) for every point in the output grid. Note that the reciprocal of the denominator of Equation (2.2) is the total variance at each point—a useful byproduct of the interpolation process. Again, *Worden et al. (2010)* provides additional details.

2.5.4 Amplify Ground Motions

At this point, ShakeMap has produced interpolated grids of ground motions (and intensities) at a site class specified as "rock." If the operator has specified the *-basement* option to *grind* (and supplied the necessary depth-to-basement file), a basin amplification function (currently *Field et al., 2000*) is applied to the grids. Then, if the user has specified *-qtm*, site amplifications are applied to the grids, creating the final output.

2.5.5 Differences in Handling MMI

The processing of MMI is designed to be identical to the processing of PGM; however, a few differences remain:

1. As of this writing, there are no spatial correlation functions available for MMI. We are working on developing one, but it is not complete. We currently use the spatial correlation function for PGA as a proxy for MMI, though this approach is not optimal.
2. Because there are relatively few IPEs available at this time, we have introduced the idea of a virtual IPE (VIPE). If the user does not specify an IPE in *grind.conf*, *grind* will use the configured GMPE in combination with the GMICE to simulate the functionality of an IPE. In particular, the bias is computed as a magnitude adjustment to the VIPE to produce the best fit to the intensity observations (and converted observations) as described in *Event Bias*; and the uncertainty of the VIPE is the combined uncertainty of the GMPE and the GMICE.
3. As mentioned above, intensity observations are given an inherent uncertainty because of the nature of their assignment. Our research has shown that this uncertainty amounts to a few tenths of an intensity unit, but it varies with the number of responses within the averaged area. Research in this area is incomplete, and intensity data can contain both "Did You Feel It?" data and traditionally assigned intensities. Because of these considerations, we currently use a conservative value of 0.5 intensity units for the inherent uncertainty.
4. The directivity function we use (*Rowshandel, 2010*) does not have terms for intensity. This is not a problem when using the VIPE, since we can apply the directivity function to the output of the encapsulated GMPE before converting to intensity. But when a true IPE is used there is currently no explicit way to apply our directivity function. In these cases, we use the VIPE to compute two intensity grids: one with and one without directivity applied. We then subtract the former from the latter to produce a grid of directivity adjustment factors. That grid is then added to the output of the IPE. We use the same procedure when creating estimates at observation locations for computing the bias.
5. As mentioned above, we currently have no function for applying basin amplification to the intensity data. We hope to remedy this shortly with a solution similar to item 4, above, where we apply the basin effects through a VIPE. In practice, the main areas where basin depth models are available are also those within which station density is great (e.g., Los Angeles and San Francisco, California).

2.5.6 Fault Considerations

Small-to-moderate earthquakes can be effectively characterized as a point source, with distances being calculated from the hypocenter (or epicenter, depending on the GMPE). But accurate prediction of ground motions from larger earthquakes requires knowledge of the fault geometry. This is because ground motions attenuate with distance from the source (i.e. fault), but for a spatially extended source, that distance can be quite different from the distance to the hypocenter. Most GMPEs are developed using earthquakes with well-constrained fault geometry, and therefore are not suitable for prediction of ground motions from large earthquakes when only a point source is available. As discussed in the *next section*, we handle this common situation by using terms that modify the distance calculation to accommodate the unknown fault geometry. We also allow the operator to specify a finite fault, as discussed in sections *Fault Dimensions* and *Directivity*.

Median Distance and Finite Faults

As discussed in the *Software Guide*, the user may specify a finite fault to guide the estimates of the GMPE, but often a fault model is not available for some time following an earthquake. For larger events, this becomes problematic because the distance-to-source term ShakeMap provides to the GMPE in order to predict ground motions comes from the hypocenter (or epicenter, depending on the GMPE) rather than the actual rupture plane (or its surface projection), and for a large fault, these distances can be quite different. For a non-point source, in fact, the hypocentral distance can equal the closest distance, but it can also be significantly greater than the closest distance.

ShakeMap addresses this issue by introducing the concept of median distance. Following a study by *EPRI (2003)*, we assume that an unknown fault of appropriate size could have any orientation, and we use EPRI's equations to compute the distance that produces the median ground motions of all the possible fault orientations that pass through the hypocenter. (Thus, the term "median distance" is a bit of a misnomer; it is more literally "distance of median ground motion.") Thus, for each point for which we want ground motion estimates, we compute this distance and use it as input to the GMPE. We also adjust the uncertainty of the estimate to account for the larger uncertainty associated with this situation. This feature automatically applies for earthquake magnitudes >= 5, but may be disabled with the *grind* flag *-nomedian*.

Ideally, GMPE developers would always regress not only for fault distance, but also for hypocentral distance. If this were done routinely, we would be able to initially use the hypocentral-distance regression coefficients and switch to fault-distance terms as the fault geometry was established. The median-distance approximation described above could then be discarded.

Bommer and Akkar (2012) have made the case for deriving both sets of coefficients: "The most simple, consistent, efficient and elegant solution to this problem is for all ground-motion prediction equations to be derived and presented in pairs of models, one using the analysts' preferred extended source metric ... —and another using a point- source metric, for which our preference would be hypocentral distance, Rhyp". Indeed, *Akkar et al. (2014)* provide such multiple coefficients for their GMPEs for the Middle East and Europe. However, despite its utility, this strategy has not been widely adopted among the requirements for modern GMPEs (e.g., *Powers et al., 2008*; *Abrahamson et al., 2008*; *2014*).

The hypocentral- or median-distance correction is not a trivial consideration. Note that for Northridge, even when the fault is unknown and there are no data, the median-distance correction (Figure 2.8 and Figure 2.9, panels B and C) brings the shaking estimates more in line with those constrained by knowledge of the fault. As mentioned earlier, the shaking for this event exhibits a positive inter-event bias term, so even with the fault location constrained, estimates still tend to under-predict the actual recordings, on average.

While the effect of this correction for the Northridge earthquake example is noticeable, for events with larger magnitudes, and thus larger rupture areas, the median-distance correction is crucial before constraints on rupture geometry are available (from finite-fault modeling, aftershock distribution, observations of surface slip, etc.) For example, in the case of the 1994 Northridge earthquake, the dimensions of the rupture are constrained from analyses of the earthquake source (e.g., *Wald et al., 1996*).

Fault Dimensions

The *Software Guide* describes the format for specifying a fault. Essentially, ShakeMap faults are one or more (connected or disconnected) planar quadrilaterals. The fault geometry is used by ShakeMap to compute fault-to-site distances for the GMPE, IPE, and GMICE, as well as to visualize the fault geometry in map view (for example, see red-line rectangles in Figure 2.8 and Figure 2.9). Examples of fault-based distances include the distance to the surface projection of the fault (for the so-called Joyner-Boore, or JB, distance), and the distance to the rupture plane.

While a finite fault is important for estimating the shaking from larger earthquakes, it is typically not necessary to develop an extremely precise fault model, or to know the rupture history that specifies the rupture propagation and slip distribution. One or two fault planes usually suffice, except for very large or complex surface-rupturing faults. In the immediate aftermath of a large earthquake, a first-order fault model based on tectonic environment, known faults, aftershock distribution, and empirical estimates based on the magnitude (e.g., *Wells and Coppersmith, 1994*) is often sufficient to greatly improve the ShakeMap estimates in poorly instrumented areas. In many cases, this amounts to an "educated guess", and seismological expertise and intuition are extremely helpful. Later refinements to the faulting geometry may or may not fundamentally change the shaking pattern, depending on the density of near-source observations. As we show in a later section, dense observations greatly diminish the influence of the estimated ground motion at each grid point, obviating the need for precise fault geometries in such estimates.

Directivity

Another way in which a finite fault may affect the estimated ground motions is through directivity. Where a finite fault has been defined in ShakeMap, one may choose to apply a correction for rupture directivity. We use the approach developed by *Rowshandel (2010)* for the NGA GMPEs (note: caution should be exercised when applying this directivity function to non-NGA GMPEs; in addition, other directivity models give significantly different results, which is an indication that there is a high degree of uncertainty in these models). For the purposes of this calculation, we assume a constant rupture over the fault surface. While the directivity effect is secondary to fault geometry, it can make a not-insignificant difference in the near-source ground motions up-rupture or along-strike from the hypocenter.

An example of the effect of the *Rowshandel (2010)* directivity term is shown clearly in Figure 2.14 for a hypothetical strike-slip faulting scenario along the Hayward Fault in the East Bay area of San Francisco. Unilateral rupture southeastward results in stronger shaking, particularly along the southern edge of the rupture. The frequency dependence of the directivity terms provided by *Rowshandel (2010)* can be examined in detail by viewing the intermediate grids produced and stored in the ShakeMap output directory. In general, longer-period IMs (PGV, PSA1.0 and PSA3.0, and MMI) are more strongly affected by the directivity function employed.

2.5.7 Additional Considerations

There are a great number of details and options when running *grind*. Operators should familiarize themselves with *grind* 's behavior by reading the *Software Guide*, the configuration file (*grind.conf*), and the program's self-documentation (run "*grind -help*"). Below are a few other characteristics of *grind* that the operator should be familiar with.

User-supplied Estimate Grids

Much of the discussion above was centered on the use of GMPEs (and IPEs) and getting the best set of estimates from them (through bias, basin corrections, finite faults, and directivity). But the users may also supply their own grids of estimates for any or all of the ground motion parameters. ShakeMap is indifferent as to the way these estimates are generated, as long as they appear in a GMT grid in the event's input directory, they will be used in place of the GMPE's estimates. (See the *Software Guide* for the specifications of these input files.) If available, the user should also supply grids of uncertainties for the corresponding parameters—if not, ShakeMap will use the uncertainties produced by the GMPE.

User-supplied input motions allow the user to employ more sophisticated numerical ground-motion modeling techniques, ones that may include, for example, fault-slip distribution and 3D propagation effects not achievable using empirical GMPEs. The PGM output grid of such calculations can be rendered with ShakeMap, allowing users to visualize and employ familiar ShakeMap products. For instance, see the ShakeCast scenario described in *Applications of ShakeMap*.

Uncertainty

As mentioned above, some of the products of *grind* are grids of uncertainty for each parameter. This uncertainty is the result of a weighted average combination of the uncertainties of the various inputs (observations, converted observations, and estimates) at each point in the output. These gridded uncertainties are provided in the file *uncertainty.xml* (see *Interpolated Ground Motion Grids* for a description of the file format).

Because we also know the GMPE uncertainty over the grid, we can compute the ratio of the total ShakeMap uncertainty to the GMPE uncertainty. For the purposes of computing this uncertainty ratio, we use PGA as the reference IM.

Continuing with the Northridge earthquake ShakeMap example, Figure 2.15 presents the uncertainty maps for a variety of constraints.

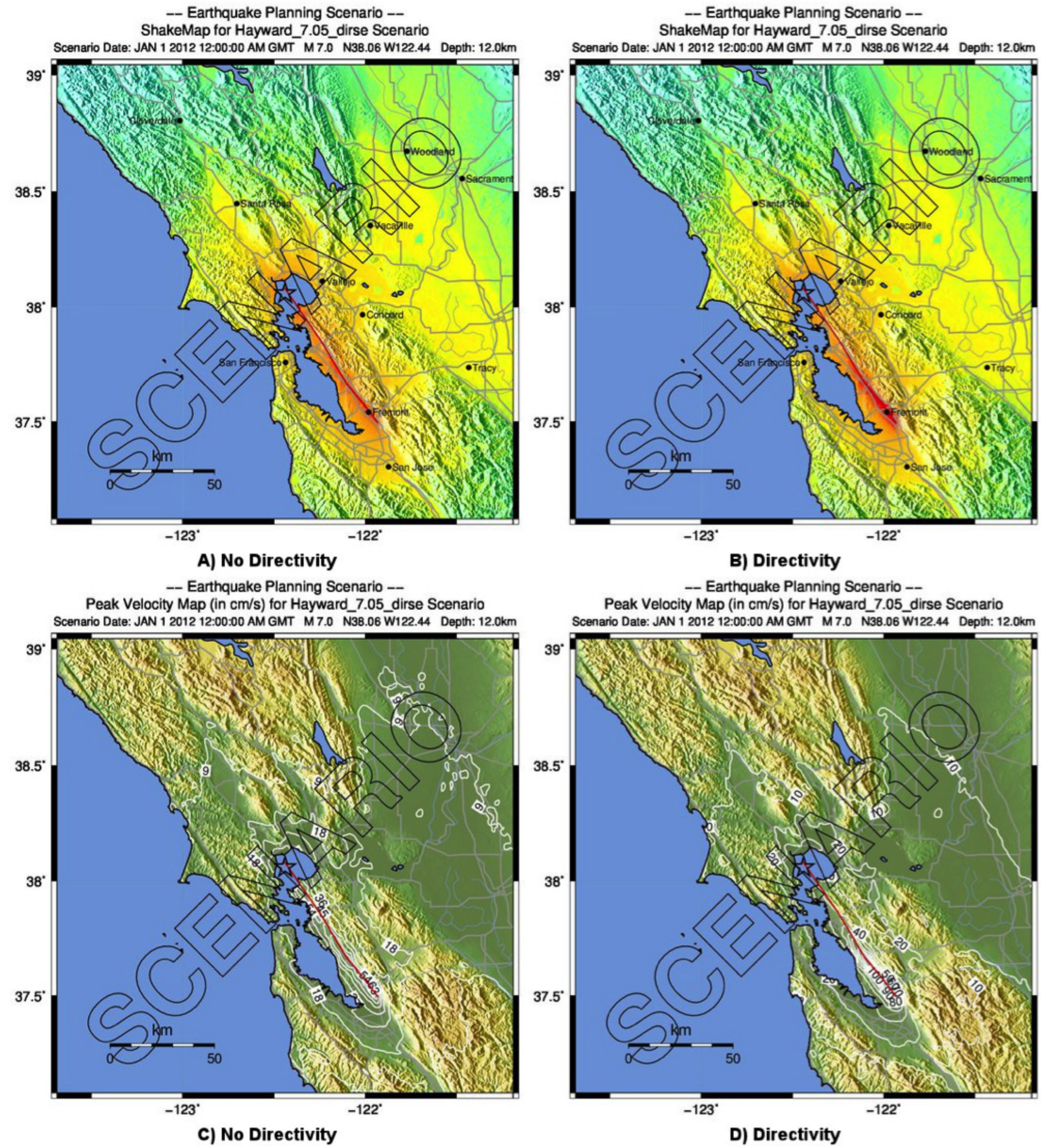


Fig. 2.14: ShakeMap scenario intensity (top) and PGV (bottom) maps for the hypothetical M7.05 Hayward Fault, CA, earthquake: A) Intensity, No directivity; B) Intensity, Directivity added; C) PGV, No Directivity; and D) PGV, Directivity added.

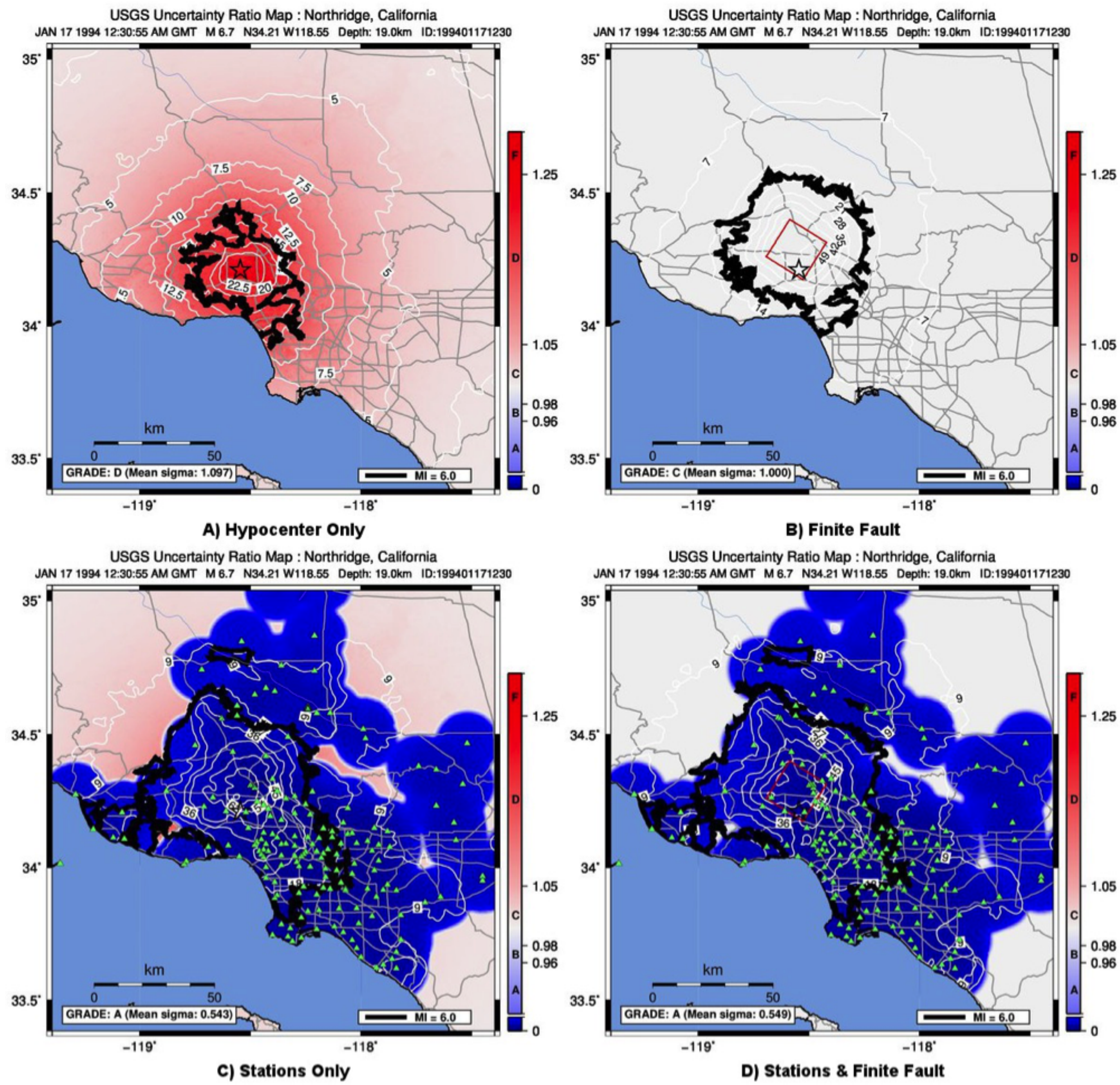


Fig. 2.15: ShakeMap uncertainty maps for the Northridge earthquake showing effect of adding a finite fault and strong motion data. Color-coded legend shows uncertainty ratio, where '1.0' indicates 1.0 times the GMPE's sigma. A) Hypocenter (black star) only; B) Finite fault (red rectangle) added but no data (mean uncertainty is 1.00 at all locations since the site-to-source distance is constrained); C) Hypocenter and strong motion stations (triangles) only (adding stations reduces overall uncertainty); and D) Finite fault and strong motion stations. Note: Average uncertainty is computed by averaging uncertainty at grids that lie within the MMI = VI contour (bold contour line), so panel (D) is marginally higher than (C) despite added constraint (fault model). For more details see *Wald et al. (2008)* and *Worden et al. (2010)*.

For a purely predictive map (of small magnitude), the uncertainty ratio will be 1.0 everywhere. For larger magnitude events, when a finite fault is not available, the ShakeMap uncertainty is greater than the nominal GMPE uncertainty (as discussed above in the section *Median Distance and Finite Faults*), leading to a ratio greater than 1.0 in the near-fault areas and diminishing with distance. When a finite fault is available, the ratio returns to 1.0. In areas where data are available, the ShakeMap uncertainty is less than that of the GMPE (see the section "Interpolation," above), resulting in a ratio less than 1.0. A grid of the uncertainty ratio (and the PGA uncertainty) is provided in the output file *grid.xml* (see *Interpolated Ground Motion Grids* for a description of this file). The uncertainty ratio is the basis for the uncertainty maps and the grading system described in the *User's Guide*.

2.6 Representing Macroseismic Intensity on Maps

Wald et al. (1999b) relates recorded ground motions to Modified Mercalli Intensities in California. While not the first work of its type, Wald et al. had the advantage of using several earthquakes that were both very well surveyed for MMI, and also well instrumented for recorded ground motions. By relating the ground motions to MMI, Wald et al. made possible the rapid calculation of expected intensities from recorded ground motions. These "instrumental intensities" could be interpolated over an area and represented on a map.

As part of the original implementation of ShakeMap, *Wald, et al. (1999a)* developed a color scale to represent expected intensities over the mapped area. This scale gives users an intuitive, easy-to-understand depiction of the ground shaking for a given earthquake. By mapping intensity to color, we also make the hardest-hit areas stand out for emergency responders and members of the media. Along with the color scale, we developed simplified two-word descriptions of the felt intensity as well as the likely damage. These abridged descriptions are not meant to replace more comprehensive descriptions provided in the MMI (e.g., *Dewey et al., 2000*; *Dewey et al., 1995*), or EMS-98 (*Grunthal et al., 1998*) scales; however, they offer convenient description for our purposes.

By relating recorded peak ground motions to Modified Mercalli Intensities, we can generate instrumental intensities within a few minutes of an earthquake. In the current ShakeMap system, these instrumental intensities can be combined with direct measures of intensity (from "Did You Feel It?", for example) and interpolated across the affected area. With the color-coding and two-word text descriptors, we can adequately describe the associated perceived shaking and potential damage consistent with both human response and damage assessments of past earthquakes to characterize the shaking from just-occurred earthquakes.

2.6.1 Color Palette for the ShakeMap Instrumental Intensity Scale

The color coding for the Instrumental Intensity map uses a standard rainbow palette (see Table 1.1). The "cool" to "hot" color scheme is familiar to most and is readily recognizable, as it is used as a standard in many fields (for example, see USA Today's daily temperature maps of the U.S.). Note that we do not believe intensity II and III can be consistently distinguished from ground-motions alone, so they are grouped together, see Figure 2.16. In addition, we saturate intensity X+ with dark red; observed ground motions alone are not sufficient to warrant any higher intensities, given that the available empirical relationships do not have any values of intensity greater than IX. In recent years, the USGS has limited observed MMIs to IX, reserving intensity X for possible future observations (see *Dewey et al., 1995*, for more details); the USGS no longer assigns intensity XI and XII. We note that there were only only two intensity-IX assignments for the 1994 Northridge earthquake (*Dewey et al., 1995*), and only two or three proper intensity-IX assignments for the 1989 Loma Prieta earthquake (J. Dewey, 2015, personal communication).

Intensity	Red	Green	Blue	Intensity	Red	Green	Blue
0	255	255	255	1	255	255	255
1	255	255	255	2	191	204	255
2	191	204	255	3	160	230	255
3	160	230	255	4	128	255	255
4	128	255	255	5	122	255	147
5	122	255	147	6	255	255	0
6	255	255	0	7	255	200	0
7	255	200	0	8	255	145	0
8	255	145	0	9	255	0	0
9	255	0	0	10	200	0	0
10	200	0	0	13	128	0	0

Table 1.1 Color Mapping Table for Instrumental Intensity. This is a portion of the Generic Mapping Tools (GMT) "cpt" file. Color values for intermediate intensities are linearly interpolated from the Red, Green, and Blue (RGB) values in columns 2-4 to columns 6-8.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Fig. 2.16: Top: ShakeMap Instrumental Intensity Scale Legend: Color palette, two-word text descriptors, and ranges of peak motions for Instrumental Intensities. Note that the peak motions are applicable to *Worden et al. (2012)*; other Ground Motion/Intensity Conversion Equations use the same color scale, but their ranges of peak motions will differ. Bottom: Legend below PGV ShakeMap. The legend for below each ShakeMap is now map (parameter-) and GMICE-specific as labeled. Color-coding of stations corresponds to their intensity the GMICE (ground motion/intensity) relationship.

We drape the color-coded Instrumental Intensity values over the topography to maximize the information available in terms of both geographic location and likely site conditions. Topography serves as a simple yet effective proxy for examining site and basin amplification, but we recognize that many users do not necessarily benefit intuitively from having topography as a basemap.

2.6.2 ShakeMap Instrumental Intensity Scale Text Descriptions

The estimated intensity map is usually wholly or partially derived from ground motions recorded by seismic instruments, and represents intensities that are likely to have been associated with the recorded ground motions. However, unlike conventional intensities, the instrumental intensities are not based on observations of the earthquake's effects on people or structures. The terms "perceived shaking" and "potential damage" in the ShakeMap legend are chosen for this reason; these intensities were not observed, but they are consistent on average with intensities at these ranges of ground motions recorded in a number of past earthquakes (see, for example, *Wald et al., 1999b*; *Worden et al., 2012*). Two-word descriptions of both shaking and damage levels are provided to summarize the effects in an area; they were derived with careful consideration of the existing descriptions in the Modified Mercalli definitions (L. Dengler and J. Dewey, written communication, 1998, 2003).

The ShakeMap qualitative descriptions of shaking are intended to be consistent with the way people perceive the shaking in earthquakes. The descriptions for intensities up to VII are constrained by the work of *Dengler and Dewey (1998)*, in which they compared results of telephone surveys with USGS MMI intensities for the 1994 Northridge earthquake. The ShakeMap descriptions up to intensity VII may be viewed as a rendering of Dengler and Dewey's Figure 7a.

The instrumental intensity map for the Northridge earthquake shares most of the notable features of the Modified Mercalli map prepared by the USGS (*Dewey et al., 1995*), including the relatively high intensities near Santa Monica and southeast of the epicenter near Sherman Oaks. However, in general, the area of intensity IX on the instrumentally derived intensity map is slightly larger than on the USGS Modified Mercalli intensity map. This reflects the fact that although much of the Santa Susanna mountains, north and northwest of the epicenter, were very strongly shaken, the region is also sparsely populated, hence, observed intensities could not be determined there. This is a fundamental difference between observed and instrumentally derived intensities: instrumental intensities will show high levels of strong shaking independent of the exposure of populations and buildings, while observed intensities only represent intensities where there are structures to damage and people to experience the earthquake.

The ShakeMap descriptions of felt shaking begin to lose meaning above intensity VII or VIII. In the *Dengler and Dewey (1998)* study, peoples' perception of shaking began to saturate in the VII-VIII range, with more than half the people at VII-VIII and above reporting the shaking as "violent" (on a scale from "weak" to "violent"). In the ShakeMap descriptions, we intensified the descriptions of shaking with increases of intensity above VII, because the evidence from instrumental data is that the shaking is stronger. But we know of no solid evidence that one could discriminate intensities higher than VII on the basis of different individuals' descriptions of perceived shaking alone.

ShakeMap is not unique in describing intensity VI as corresponding to strong shaking. In the 7-point Japanese macroseismic scale, for which intensity 4 is equivalent to MMI VI, intensity 4 is described as "strong." In the European Macroseismic Scale (*Grunthel et al., 1998*) (EMS-98), which is compatible with MMI (*Musson et al., 2010*), the bullet description of intensity V is "strong." Higher EMS-98 intensities are given bullet descriptions in terms of the damage they produce, rather than the strength of perceived shaking.

2.6.3 ShakeMap Intensity Scale and Peak Ground Motions

The ShakeMap Instrumental Intensity Scale Legend provides the PGA and PGV associated with the central value in each intensity box (see Figure 2.16). For all current GMICEs, the ground motion scale is logarithmic, with an increase of one intensity unit resulting from approximately a doubling of peak ground motion. Nevertheless, each GMICE has its own mapping of ground motion to intensity, and thus the values shown in the scale legend can vary, depending on the GMICE chosen for the map in question. To avoid confusion, the legends now have a citation in the lower left specifying which GMICE was used to produce the map and scale. Note, however, that while the mapping of ground motion to intensity varies, the mapping of color to intensity remains the same for all maps.

We note that the ShakeMap legends (e.g., Figure 2.16) have evolved slightly from the earlier version of ShakeMap and the 2005 ShakeMap Manual. The PGMs tabulated are no longer provided by (previously redundant) PGM ranges, but rather by the median motions associated with the intensity on the scale.

2.6.4 Color Coding Stations by Intensity

Traditionally, stations on the PGM ShakeMaps were color-coded to the seismic network that provided them. More recent versions of ShakeMap, however, allow the operator to color the stations with the intensity they produced, with each PGM parameter (e.g., PGA, PGV, PSA03) using its own intensity correlation. Figure 2.17 (and many of the other figures throughout this guide) illustrates the color coding of stations by their intensity values for several parameters. The operator can elect this option by calling the program *mapping* with the flag *-pgminten*.

2.7 Discussion of Chosen Map Parameters (Intensity Measures)

2.7.1 Use of Peak Values Rather than Mean

With ShakeMap, we chose to represent peak ground motions as recorded. We depict the larger of the two horizontal components, rather than as either a vector sum, or as a geometric mean value. The initial choice of peak values was necessitated by the fact that roughly two-thirds of the TriNet (now the Southern California portion of CISN) strong-motion data (the California Geological Survey, or CGS, data) are delivered as peak values for individual components of motion, that is, as parametric data rather than waveforms. This left two options: providing peak values or median of the peak values—determining vector sums of the two horizontal components was not an option, because the peak values on each component do not necessarily occur at the same time. A useful strategy going forward may be to employ the 50th percentile of the response spectra over all non-redundant rotation angles (RotD50; *Boore, 2010*), which is becoming a standard for "next-generation" GMPEs (*Abrahamson et al., 2014*), or on another agreed-upon vector-component calculation. (See *Future Directions*). However, such changes would require adoption of these calculations on the part of each contributing seismic network, and would thus require consensus (and substantial software upgrades) all around.

Despite the common use of mean values in attenuation relations and loss estimation, we decided that computing and depicting median values, which effectively reduces information and discards the largest values of shaking, was not acceptable. This is particularly true for highly directional near-fault pulse-like ground motions, for which peak velocities can be large on one component and small on the other. Mean values for such motions (particularly when determined in logarithmic space) can seriously underrepresent the largest motion that a building may have experienced, and these pulse-like motions are typically associated with the regions of greatest damage. Thus, we chose peak ground motions as the parameters to be mapped.

Beyer and Bommer (2006) provide statistical relationships to convert among median and peak parameters and between aleatory variability for different definitions of the horizontal component of motion. This is useful when approximating alternative components than those presented, but one must recognize that for any individual record, these statistics may or may not be representative.

Initially, our use of PGA and PGV for estimating intensities was also simply practical. We were retrieving only peak values from a large subset of the network, so it was impractical to compute more specific ground-motion parameters, such as average- response spectral values, kinetic energy, cumulative absolute velocities (CAV, *EPRI, 1991*), or the JMA intensity algorithm (*JMA, 1996*). However, because near-source strong ground motions are often dominated by short-duration, pulse-like ground motions (usually associated with source directivity), PGV appears to be a robust measure of intensity for strong shaking. In other words, the kinetic energy (proportional to velocity squared) available for damage is well characterized by PGV. In addition, the close correspondence of the JMA intensities and peak ground velocity indicates that our use of peak ground velocities for higher intensities was consistent with the algorithm used by JMA. Work by *Wu et al. (2003)* indicates a very good correspondence between PGV and damage for data collected on the island of Taiwan, which included high-quality loss data and densely sampled strong-motion observations for the 1999 Chi-Chi earthquake. More recent work on Ground-Motion/Intensity Conversion Equations (GMICEs) (e.g., *Atkinson and Kaka, 2007*; *Worden, et al., 2012*) has also confirmed the strong relationship between PGV and intensity.

Nonetheless, for large, distant earthquakes, peak motions may be less informative, and spectral content and perhaps duration become key parameters. Although we may eventually adopt corrections for these situations, it is difficult to assign intensities in such cases. For instance, it is difficult to assign the intensity in the zone of Mexico City where numerous high-rises collapsed during the 1985 Michoacan earthquake. There was obviously high- intensity shaking for high-rise buildings; however, most smaller buildings were unaffected, suggesting a much lower intensity. Whereas PGVs were moderate and would imply intensity VIII, resonance and duration conspired to cause a more substantial damage than peak values would indicate. Although this is, in part, a shortcoming of using peak parameters alone, it is more a limitation imposed by simplifying the complexity of ground motions into a single parameter. Therefore, in

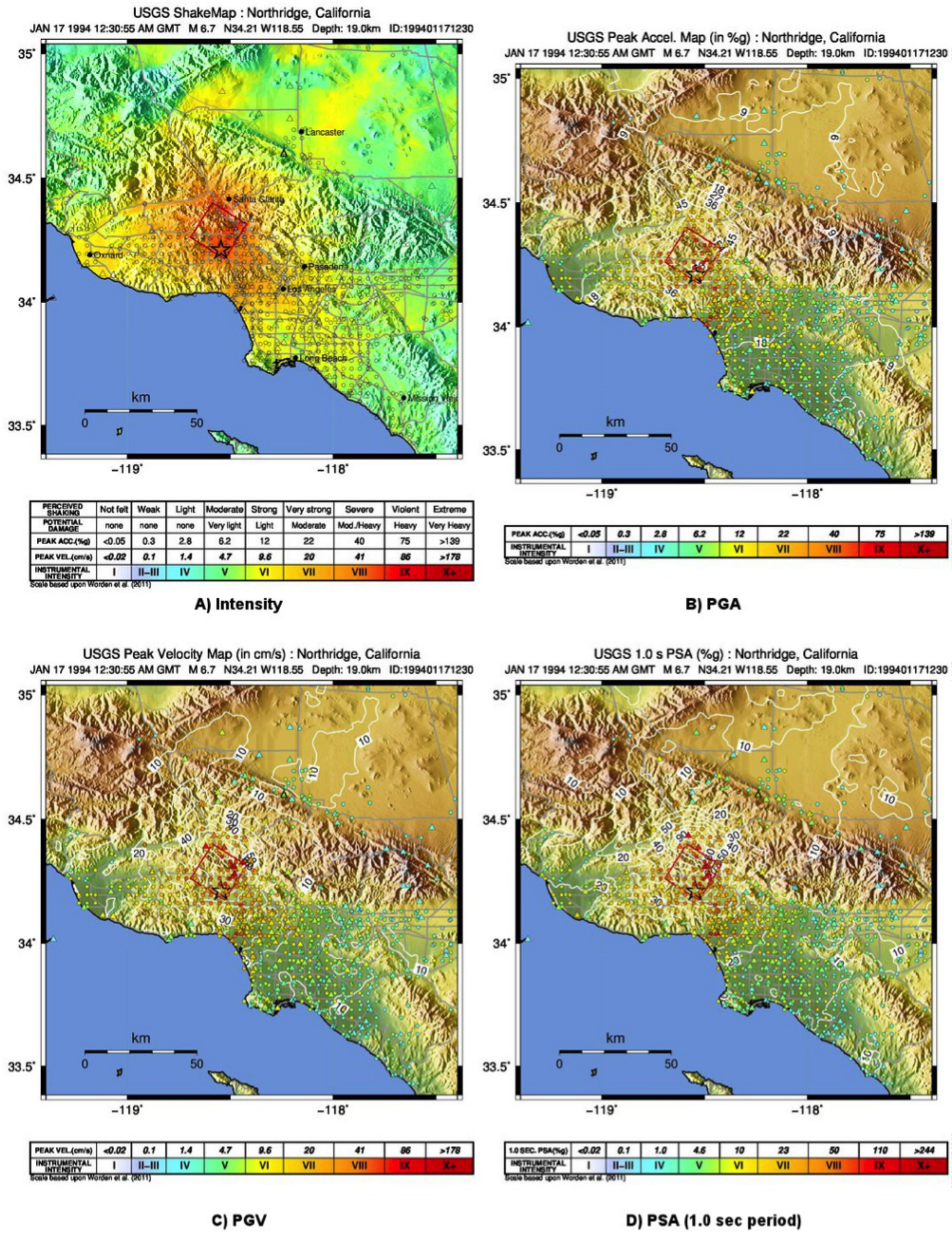


Fig. 2.17: ShakeMap for the 1994 M6.7 Northridge, CA earthquake with a finite fault (red rectangle), strong motion data (triangles) and intensity data (circles). Stations and macroseismic data are color coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Worden et al. (2011)* and indicated by the scales shown. Note: Macroseismic data do not change colors from map to map, but seismic stations do, since the estimated intensity conversion depends on which parameter is used.

addition to providing peak ground-motion values and intensity, we are also producing spectral response maps (for 0.3, 1.0, and 3.0 sec). Users who can process this information for loss estimation will have a clearer picture than can be provided with maps of PGA and PGV alone. However, as discussed earlier, a simple intensity map is extremely useful for the overwhelming majority of users, which includes the general public and many people involved with the initial emergency response.

CHAPTER

THREE

USER'S GUIDE

ShakeMap originated primarily as an internet-based system to provide real-time displays of earthquake shaking. Although the online color-coded intensity maps are the most visible result of the ShakeMap system and are the most commonly accessed and downloaded products, they are just one representation of the ShakeMap output. ShakeMap also produces grids of peak ground acceleration (PGA) and velocity amplitudes (PGV), peak spectral response values (PSA), instrumental intensities, seismic station files, fault files, regression plots, contours, metadata, and uncertainty estimates. The ShakeMap webpages also serve a variety of formats, including PDF, KML, XML, GeoJSON, HAZUS-MH, GIS files, ESRI Raster, and a host of other formats and products for varied user needs and applications.

In this User's Guide, after some background, we present the range of ShakeMap products and describe the available formats. The different automated mechanisms to receive and utilize ShakeMap—including GIS Web Services, GeoJSON feeds, and ShakeCast—are described and links are provided. Many users also take advantage of real-time ShakeMaps, as well as older events and earthquake planning scenarios, so we describe the three primary ShakeMap repositories: real-time ShakeMaps, historic ShakeMap Atlas events, and collections of Scenario ShakeMaps.

Next is an overview of the current ShakeMap users and applications. Beyond quickly assessing the overall domain of shaking, ShakeMap is used across many sectors: planning and response, loss estimation, financial services, education and outreach, and engineering and seismological research. We provide examples of each. The section that follows expands on how ShakeMap integrates with the related systems of DYFI, ShakeCast, and PAGER. Lastly, and importantly, are *Disclaimers* that users should be aware of and refer to when employing ShakeMap as part of their post-earthquake decision making.

3.1 Background

Until the development of ShakeMap, the most common information available immediately following a significant earthquake was typically its magnitude and epicenter. However, the damage pattern is not a simple function of these two parameters alone, and more-detailed information must be provided to properly assess the hazard. For example, for the 1971 M6.7 San Fernando, California earthquake, the northern San Fernando Valley was the region with the most damage, even though it was more than 15km from the epicenter. Likewise, areas strongly affected by the 1989 M6.9 Loma Prieta and 1994 M6.7 Northridge, California, earthquakes that were either distant from the epicentral region or out of the immediate media limelight were not fully appreciated until long after the initial reports of damage. The full extent of damage from the 1995 M6.9 Kobe, Japan, earthquake was not recognized by the central government in Tokyo until many hours later (e.g., *Yamakawa, 1998*), seriously delaying rescue and recovery efforts.

In contrast, a ShakeMap is a representation of actual ground shaking produced by an earthquake. The information it presents is different from the earthquake magnitude and epicenter that are released after an earthquake, because ShakeMap focuses on the ground shaking produced by the earthquake, rather than the parameters describing the earthquake starting point (its hypocenter) and size (magnitude). So, although an earthquake has one magnitude and one epicenter, it produces a range of ground shaking levels at sites throughout the region, depending on distance from the earthquake fault that ruptured, the rock and soil conditions at sites, and variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth's crust.

Part of the strategy for generating rapid-response ground motion maps was to determine the best format for reliable presentation of the maps given the diverse audience, which includes scientists, businesses, emergency response agencies, media, and the general public. In an effort to simplify and maximize the flow of information to general users, we have developed a means of generating not only PGA and PGV maps, but also an instrumentally derived estimated Modified Mercalli Intensity (MMI) map. This "instrumental intensity" map makes it easier to relate the recorded ground motions to the expected felt area and damaging shaking distribution. At the same time, we preserve a full range of utilities of recorded ground-motion data by producing maps of response spectral acceleration, which are not particularly useful to the general public, yet which provide fundamental data for loss estimation and earthquake engineering assessments.

As mentioned, ShakeMap provides maps of **peak** ground-acceleration, velocity, and spectral acceleration as well as MMI. Intensity ShakeMaps depict estimated intensities derived from peak ground motions as well as (optionally) from reported intensities. Intensity maps make it easier to relate the recorded and estimated ground motions to the expected felt and damage distributions. Intensities are estimated from ground shaking using equations based on analyses of intensities reported near recorded seismic stations for past earthquakes, e.g., *Wald et al. (1999b)* or *Worden et al. (2012)*. The legend on the ShakeMap indicates which relationship was used to estimate intensities from ground motions and vice versa (see the ShakeMap *Technical Guide* for more details).

Station locations are the best indicator of where the map is most accurate: near seismic stations, the shaking is well constrained by data; far from such stations, the shaking is estimated using standard seismological inferences and geospatial interpolation. Details about the interpolation; uncertainty maps; and codes for the seismic station components, network contributors, and potential outlier or clipped flag codes are provided in the *Technical Guide*. Peak horizontal acceleration and spectral acceleration values are in units of percent-g (or %g, where g = acceleration due to the force of gravity = 981cm/s/s). The peak values of the vertical components are not used in the construction of the maps. Peak velocity values are given (in cm/s) at each station. Acceleration spectra are the response of a 5% critically damped, single-degree-of-freedom oscillator to the recorded ground motion at three reference periods: 0.3, 1.0, and 3.0 sec.

3.2 Products and Formats

ShakeMap is fundamentally a geographic product, providing a spatial representation of the potentially very complex shaking field associated with an earthquake. Because of its complicated nature, we are required to generate numerous maps that portray various aspects of the shaking that are customized for specific uses or audiences. For some uses, it is not the maps themselves but the components that make up the ShakeMaps that are of interest in order to re-create or further customize the maps or user-specific products. In this section, we further describe these ShakeMap component products and the variety of maps and formats.

For each earthquake, all maps and associated products for that event are available via the "Downloads" link on each earthquake-specific ShakeMap webpage.

3.2.1 Input Files

The downloadable products include sufficient information to reproduce the ShakeMap. In particular, *stationlist.xml* and the **_fault.txt* file(s) provide the input files, *grid.xml* provides the Vs30 grid (see above), and *info.xml* provides the important configuration and processing parameters, including the name(s) of the fault file(s).

Station Lists. The file *stationlist.xml* contains the combined input data from all of the original processing center's input files in a ShakeMap-readable format. The file may contain seismic station data, intensity data, or a combination of both. The file also contains an event tag with the earthquake source specifications. See the ShakeMap *Software & Implementation Guide* for a complete specification of the ShakeMap-input XML formats.

For reasons of backward compatibility, we also provide *stationlist.txt*. As with *grid.xyz*, the use of this file is deprecated and it may disappear in a future release.

Fault Files. Fault files are named *<something>_fault.txt* and are listed in *info.xml*. Zero or more fault files may be present in the ShakeMap input directory. See the ShakeMap *Software & Implementation Guide* for a complete specification of the fault file format. For the purposes of reproducing the ShakeMap for an earthquake, it is sufficient to copy the specified file(s) into the event's input directory.

3.2.2 Output Files and Products

The available ShakeMap products include (and each is described in more detail in the sections that follow):

- **Metadata and runtime information**
  - FGDC-compliant metadata
  - XML file of processing and constraints parameters, input data, output paramaters, timestamps, and versioning.
- **Static maps and plots (images)**
  - Macroseismic Intensity
  - Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Pseudo-Spectral Acceleration (PSA) (when appropriate)
  - Uncertainty maps
  - Regression (GMPE) plots
  - Station lists
- **Interactive maps**
- **Grids of interpolated ground shaking**
  - XML grid of ground motions
  - XML grid of ground motions on "rock"
  - XML grid of ground-motion uncertainty
  - Text grid of ground motions (deprecated)
- **GIS files**
  - GIS Shapefiles
  - HAZUS-MH® Shapefiles
  - ESRI Raster Grid Files
  - Google Earth KML files
  - Contour Files

Metadata and Runtime Information

Metadata. FGDC-compliant geospatial metadata files are distributed via the earthquake-specific ShakeMap webpage for each earthquake under the "Downloads" page. The metadata are provided in text, HTML, and XML formats in the files *metadata.txt*, *metadata.html*, and *metadata.xml*, respectively.

Because the ShakeMap output grid is the fundamental derived product from the ShakeMap processing, it is fully described in an accompanying metadata file following Federal Geographic Data Committee (FGDC) standards for geospatial information. As described below, station amplitudes are provided in separate ShakeMap station files; however, the complete metadata for the parametric data are archived by the regional seismic networks and contributing strong-motion data sources.

Supplemental Information. A second aggregation of important earthquake-specific ShakeMap information is provided online in the file *info.xml*. This supplemental information provides a machine-readable (XML) rundown of many important ShakeMap processing parameters. It includes information about the data and fault input files; the source mechanism; the GMPE, IPE, and GMICE selected; the type and source of the site amplifications; the map boundaries; and important output information, including the bias and maximum amplitude for each parameter. The *info.xml* is critical for understanding or replicating any particular ShakeMap.

Note: Timestamps, versions of the ShakeMap software employed, event-specific parameters, and the version of the specific ShakeMap run are documented in the supplemental information provided in the *info.xml* file.

Static Maps and Plots (Images)

ShakeMap generates a number of static ground-motion maps and plots for various parameters (intensity measures, or IMs). Most of these maps are available in JPEG format, as well as zipped PostScript files that—as vector-based images—are suitable for PDF conversion or editing. These maps are typically generated automatically, limiting the format, extent, and features that can be depicted. Nonetheless, these static maps are ShakeMap's "signature products" and serve as maps of record and for other purposes, as described below. Static maps can be accessed and selected using tabs along the top of the USGS earthquake event page, as shown in the example in Figure 3.1.

Intensity Maps. Intensity images—typically of Modified Mercalli Intensity (MMI), but potentially other intensity measures—are the most familiar ShakeMap products. The main intensity map consists of a colored overlay of intensity with the epicenter (and the causative fault, if supplied) prominently marked, (usually) overlain upon the region's topography, with other cultural and geologic features (cities, roads, and active faults) plotted, depending on the configuration of the ShakeMap system. A detailed scale of intensity is also provided as described in detail in the *Technical Guide*.

Note: ShakeMap Symbology. It is a recent ShakeMap convention to depict seismic stations as **triangles** and intensity observations as **circles** (for cities) or **squares** (for geocoded boxes). On intensity maps, symbols are unfilled so that the underlying intensity values are visible. On peak ground motion maps, observations are (optionally) color coded to their amplitude according to the legend shown below each map. The epicenter is indicated with a **star**, and for larger earthquakes, the surface projection of the causative fault is shown with **black lines**.

Strong motion and intensity data symbols default to "see-through" (unfilled) mode for the intensity map shown in Figure 3.2 and are color-filled for peak ground motion maps (Figure 3.3). ShakeMap operators may chose to modify these defaults using alternative mapping configurations.

Peak Ground Motion Maps. ShakeMap generates static maps for PGA, PGV, and Intensity, and optionally, three separate maps for PSA (at 0.3, 1.0, and 3.0 sec). The PGM maps are distinct from the intensity maps: shaking values on the former are colored image overlays; the latter are PGM contours. On PGM maps, stations' fill colors indicate the ground motion of the station converted to intensity or, optionally, the identity of the seismic network data source. When the color indicates peak ground motion, the values are converted to the intensity color scheme via the selected ground-motion–intensity conversion equation (GMICE), and the corresponding color scale bar is provided at the bottom of the map (see example in Figure 3.3).

Interactive Maps

Although the static ShakeMaps are useful, many of these products are more suitably served as interactive maps which can be dynamically scaled (zoomed) and layered upon with user-selected background and other overlays. The layers

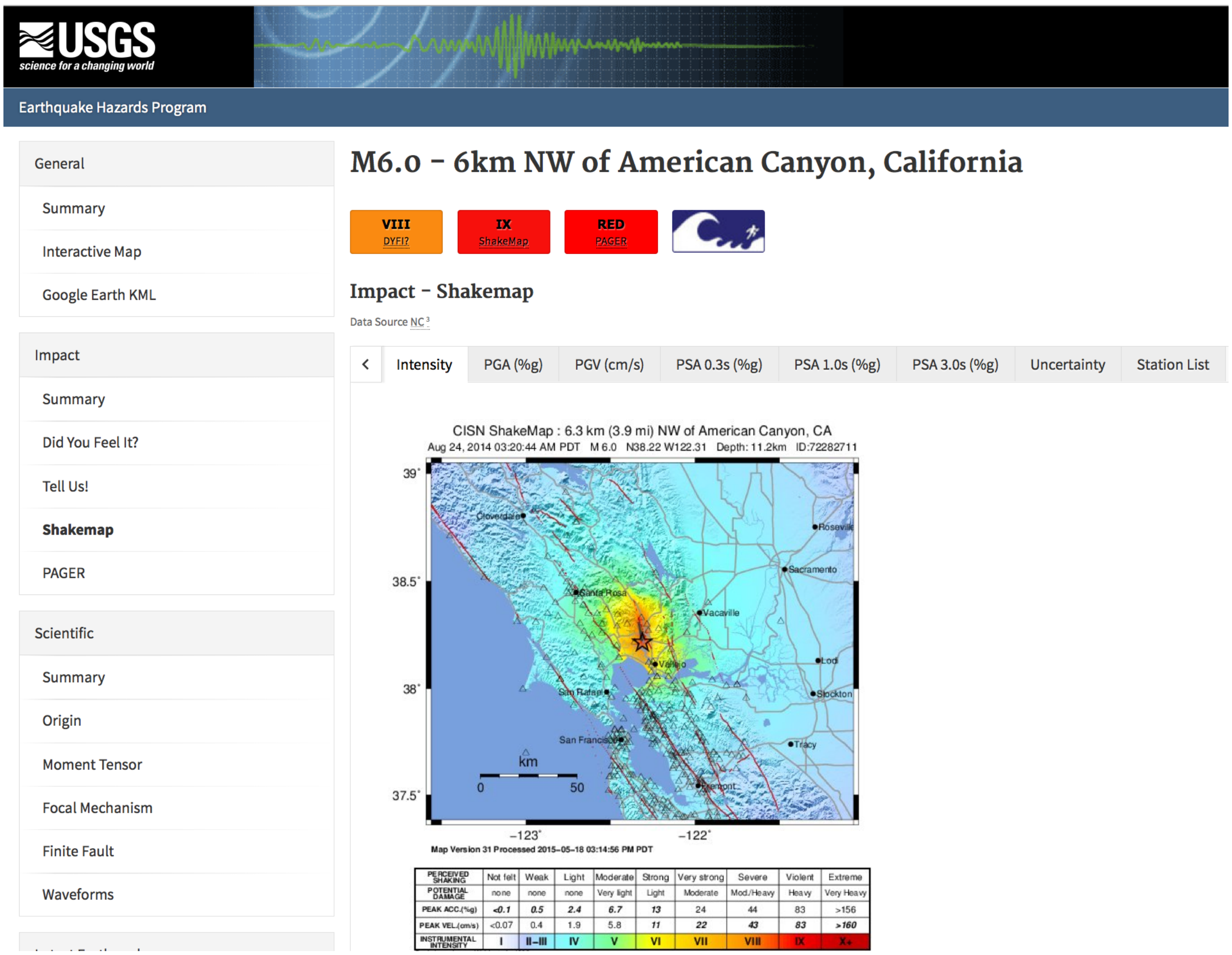
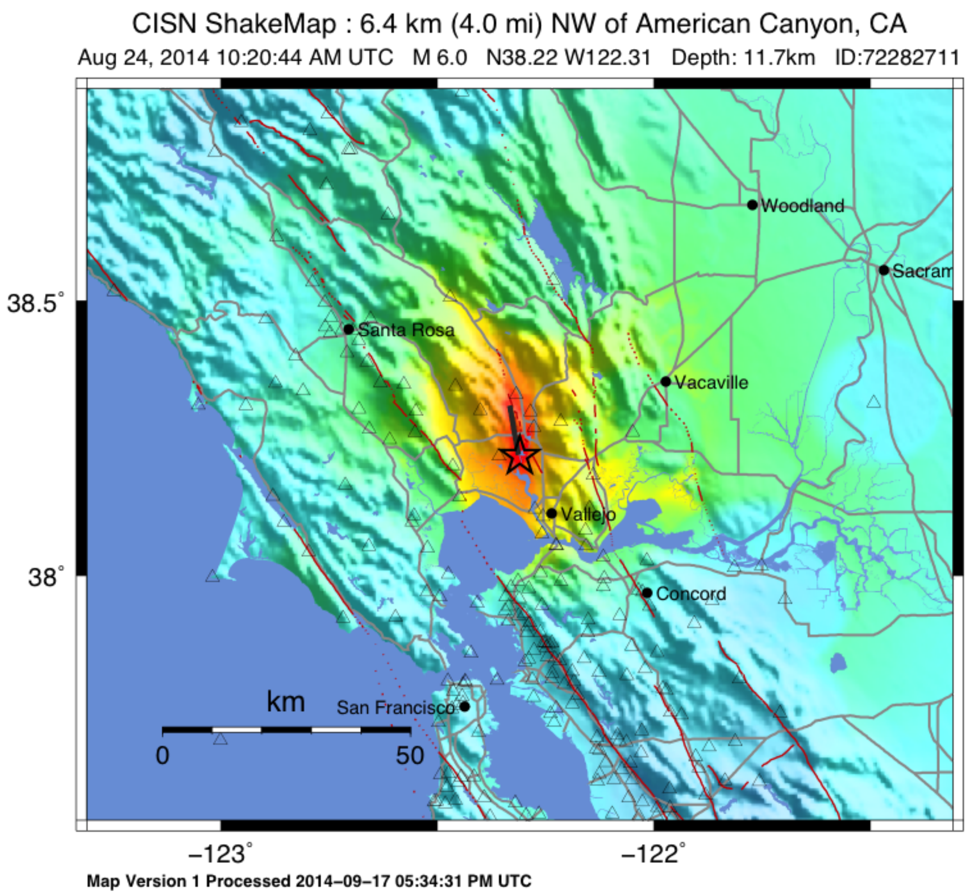


Fig. 3.1: Event page ShakeMap view for the 2014 M6.0 American Canyon (Napa Valley), CA earthquake. The static instrumental intensity map is shown. Tabs above the map allow access and comparison of different intensity measures (IMs), as well as the uncertainty map and station list.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Fig. 3.2: Intensity ShakeMap from the 2014 M6.0 American Canyon (Napa Valley), CA earthquake. Strong-motion data (triangles) and intensity data (circles) default to "see-through" mode for the intensity map. The north-south black line indicates the fault location, and the epicenter is a red star. The intensity color-coding either as observed (for macroseismic data) or as converted is derived from the conversion equations of *Wald et al. (1999b)* as shown in the legend. Note: Map Version Number reflects separate offline processing for this Manual.

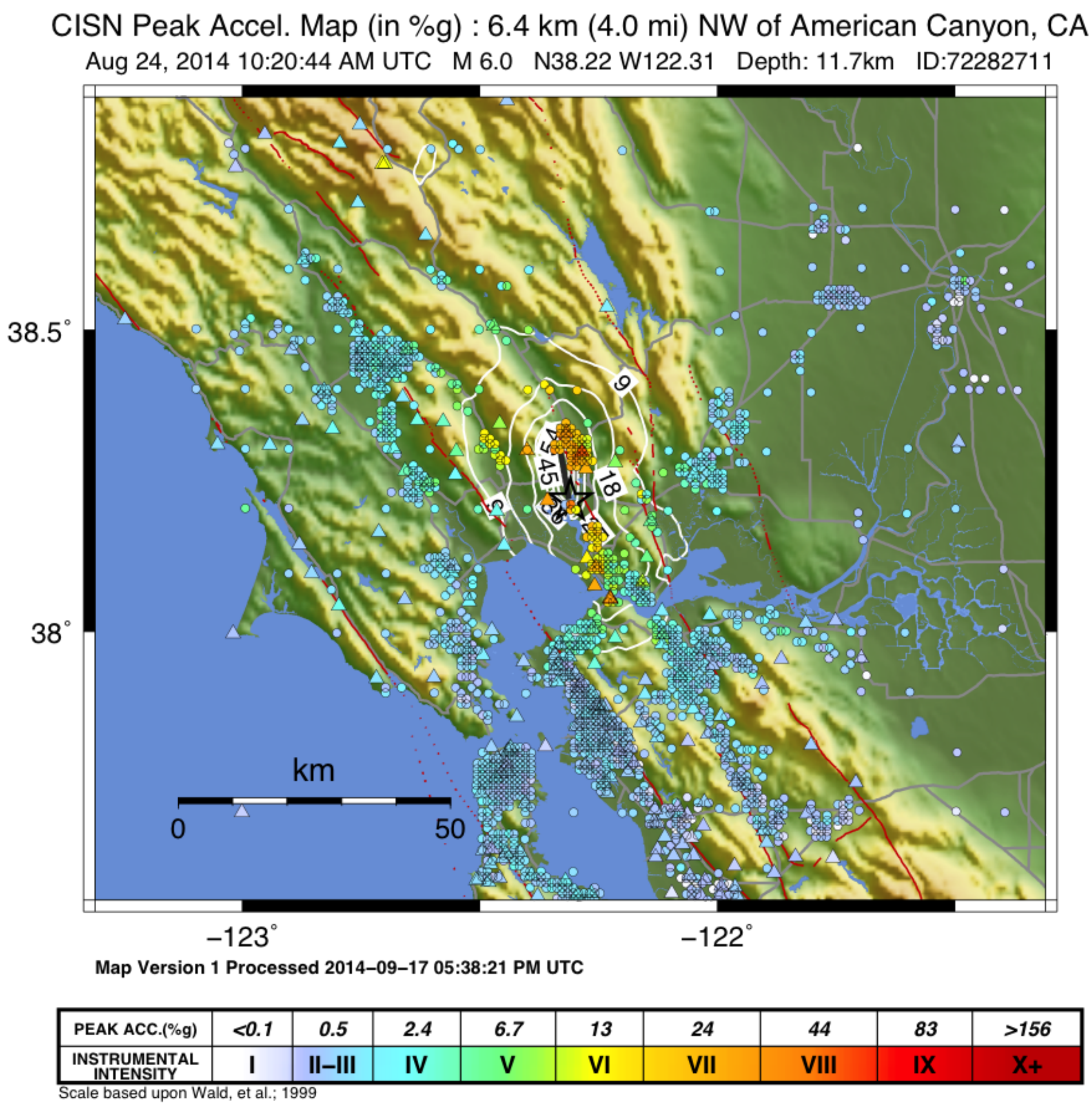


Fig. 3.3: Peak acceleration ShakeMap from the 2014 M6.0 American Canyon (Napa Valley), CA earthquake. Strong-motion data (triangles) and intensity data (circles) are color-coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Wald et al. (1999b)* as shown in the legend. The north-south black line indicates the fault location, which nucleated near the epicenter (red star). Note: Map Version Number reflects separate offline processing for this Manual.

are provided via GeoJSON, KML, GIS, Raster, and other formats. The USGS Earthquake Program Web pages employ Leaflet, an open-source JavaScript library that is suitable for mobile-friendly interactive maps (see, for example, Figure 3.4). Many of the interactive features are geared towards balancing the experience for both desktop and mobile visitors (Figure 3.5). Since the interactive maps are zoomable, it is convenient to select individual stations to query station information and amplitudes (see the example in Figure 3.6). The interactive map also allows users to select and show/hide specific layers, including seismic stations and DYFI geocoded intensity stations (Figure 3.7).

Fig. 3.4: Interactive ShakeMap for the 2014 M6.0 American Canyon, CA earthquake. Contours indicate intensities; strong motion data (triangles) and intensity data (circles) are color-coded according to their intensity value, either as observed (for macroseismic data) or as converted by *Worden et al. (2012)*.

The interactive maps may be accessed by clicking on the static ShakeMaps on the USGS event pages (e.g., http://earthquake.usgs.gov/earthquakes/eventpage/us10003zgz#impact_shakemap).

Note: Currently, interactive maps only portray contours of intensity. Other contours can be downloaded for users' programs, or overlain with the GIS or KML formats provided with each ShakeMap.

Uncertainty Maps. As discussed in detail in the *Technical Guide*, gridded uncertainty is available for all ground

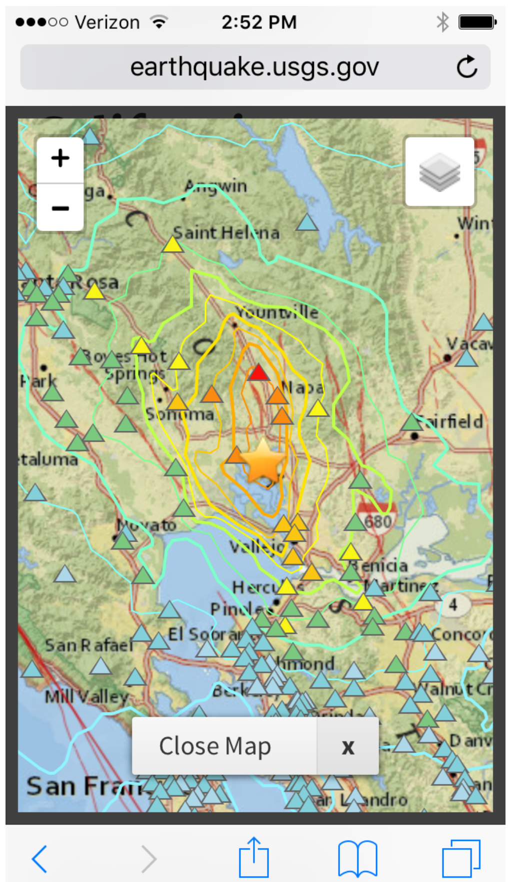


Fig. 3.5: Mobile view of the interactive ShakeMap for the 2014 M6.0 American Canyon, CA earthquake. Contours indicate intensities; strong motion data (triangles) are color-coded according to their intensity value.

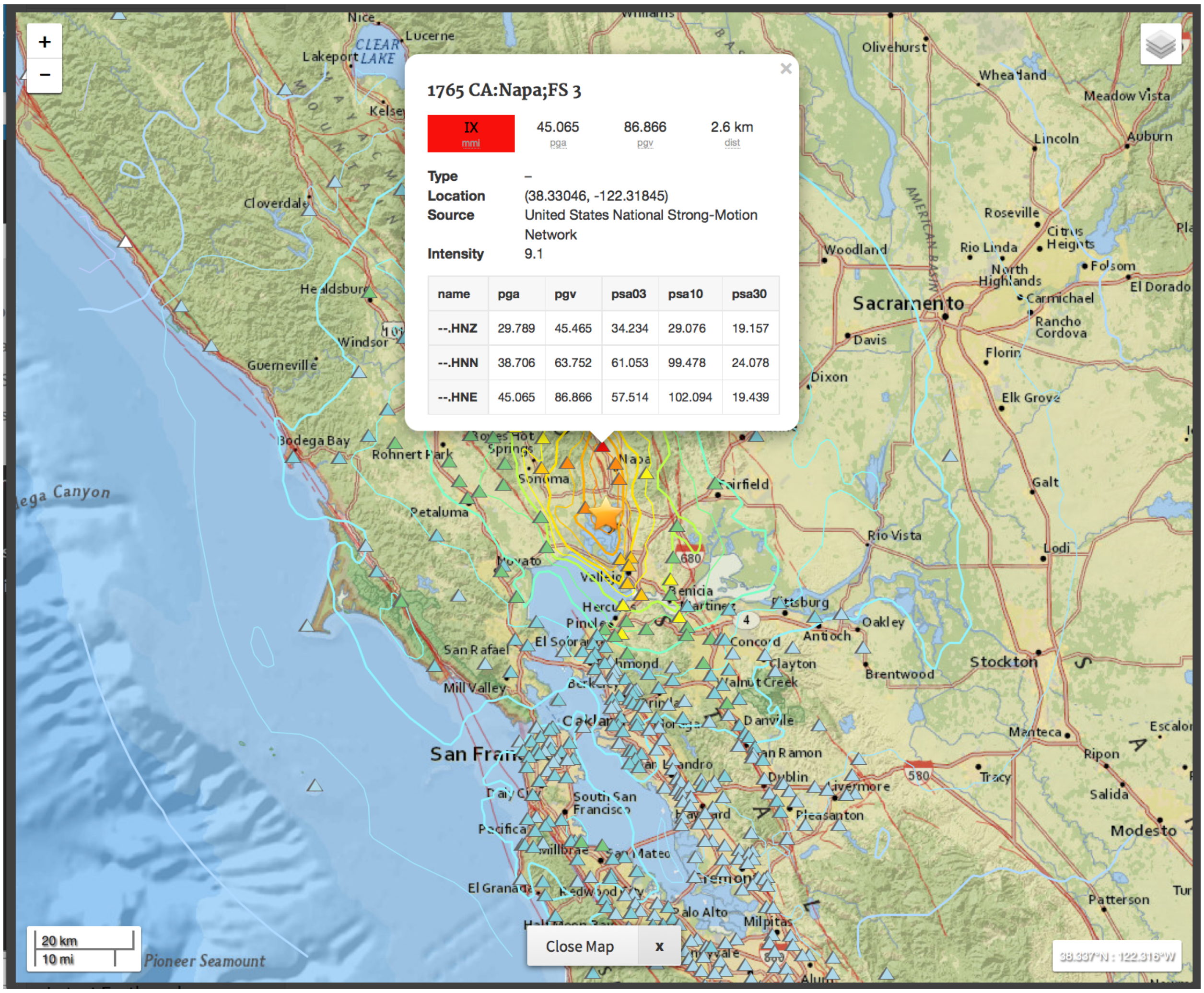


Fig. 3.6: Interactive ShakeMap for the 2014 M6.0 American Canyon, CA earthquake showing station information pop-up.

Fig. 3.7: Interactive ShakeMap for the 2014 M6.0 American Canyon, CA earthquake. On the interactive map, reported (DYFI) intensities are geocoded and represented with **squares** depicting the 1km grid area they occupy. Reported Intensities are color-coded according to their intensity value, either as observed or as converted by *Wald et al. (1999b)*.

motion parameters. The ratio of the ShakeMap PGA uncertainty to the GMPE's uncertainty is also available (see the section on *Interpolation*).

We utilize the uncertainty ratio to produce a graded map of uncertainty. Where the ratio is 1.0 (meaning the ShakeMap is purely predictive), the map is colored white. Where the ratio is greater than 1.0 (meaning that the ShakeMap uncertainty is high because of unknown fault geometry), the map shades toward dark red, and where the uncertainty is less than 1.0 (because the presence of data decreases the uncertainty), the map shades toward dark blue. These maps provide a quick visual summary of the quality of ground-motion estimates over the area of interest.

ShakeMaps are also given a letter grade based on the mean uncertainty ratio within the area of the MMI-VI contour (on the theory that this is the area most important to accurately represent). A ratio of 1.0 is given a grade of "C"; maps with mean ratios greater than 1.0 get grades of "D" or "F"; ratios less than 1.0 earn grades of "B" or "A". If the map does not contain areas of MMI >= VI, no grade is assigned. See Figure 3.8 for an example uncertainty map.

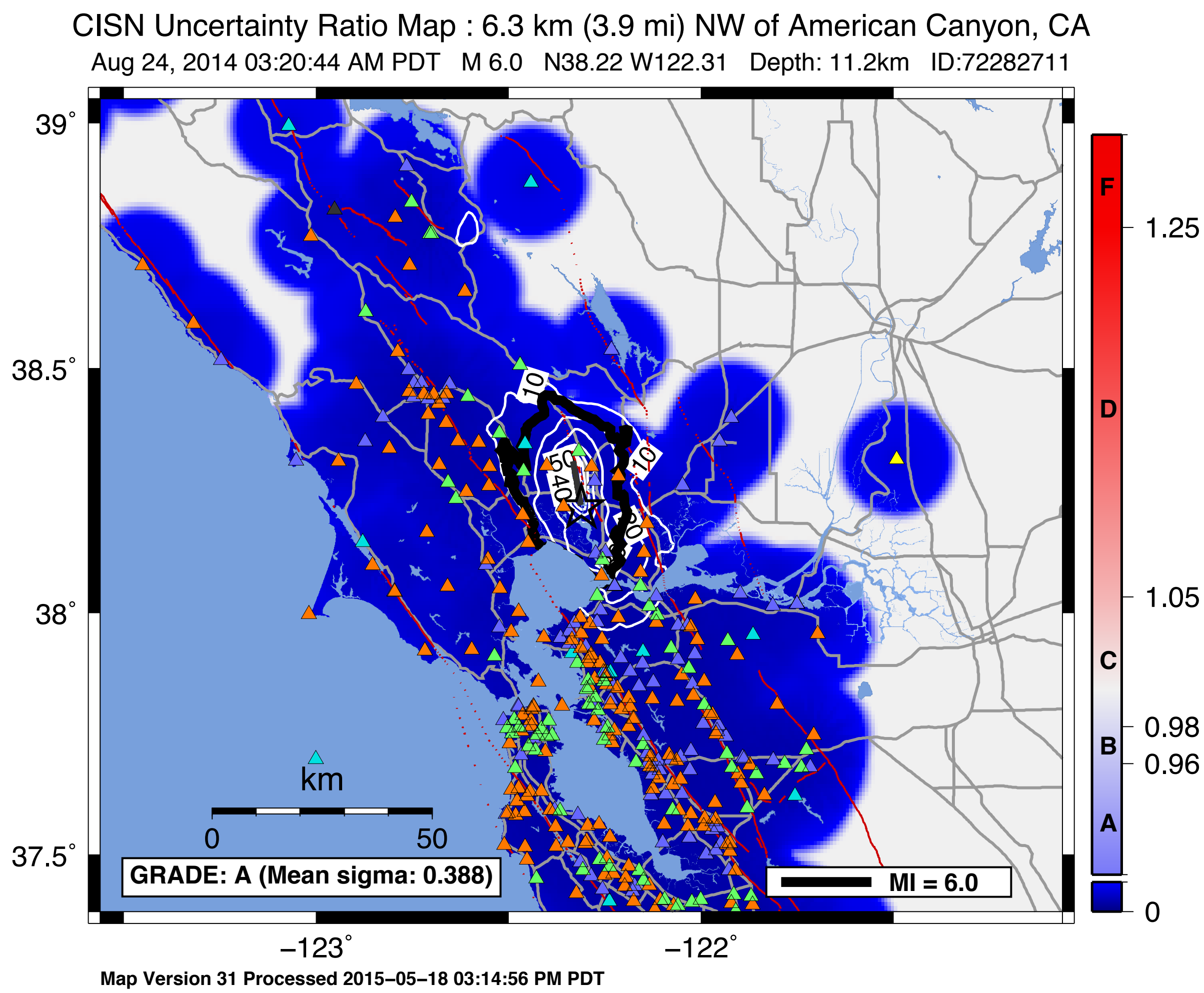


Fig. 3.8: ShakeMap uncertainty map for the 2014 M6.0 American Canyon, CA earthquake. Color-coded legend shows uncertainty ratio, where "1.0" indicates 1.0 times the GMPE's sigma. The average uncertainty is computed by averaging uncertainty at grid points that lie within the MMI-VI contour (bold contour line). For more details, see *Wald et al. (2008)*, *Worden et al. (2010)*, and the *Technical Guide*.

Regression (GMPE and Distance Attenuation) Plots.

ShakeMap can also (optionally) produce graphs of the observational data plotted with the biased and unbiased GMPE. For example, Figure 3.9 shows the 1994 M6.7 Northridge earthquake MMI data, and Figure 3.10 shows the PGA data and GMPE.

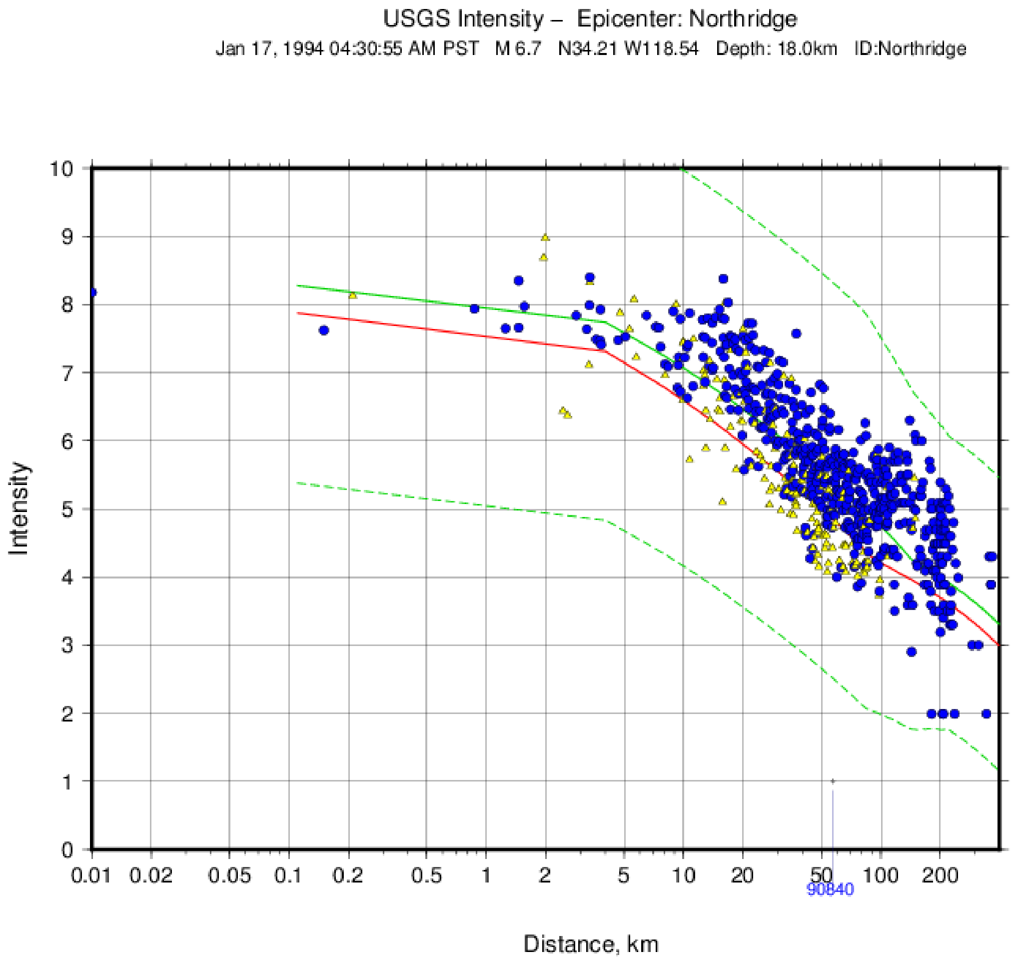


Fig. 3.9: Plot showing the 1994 M6.7 Northridge, CA earthquake MMI data (seismic stations are yellow triangles; DYFI observations are blue circles) plotted with the unbiased (red line) and biased (green line) IPE. The dashed green lines show the biased IPE ±3 standard deviations.

Interpolated Ground Motion Grids

As described in the *Technical Guide*, the fundamental output product of the ShakeMap processing system is a finely-sampled grid (nominally 1km spacing) of latitude and longitude pairs with associated amplitude values of shaking parameters at each point. These amplitude values are derived by interpolation of a combination of the recorded ground shaking observations and estimated amplitudes, with consideration of site amplification at all interpolated points. The resulting grid of amplitude values provides the basis for generating color-coded intensity contour maps, for further interpolation to infer shaking at selected locations, and for generating GIS-formatted files for further analyses.

XML Grid. The ShakeMap XML grid file is the basis for nearly all ShakeMap products, as well as for computerized post-processing in systems such as ShakeCast and PAGER [see *Related Systems*]. The XML grid is available as both

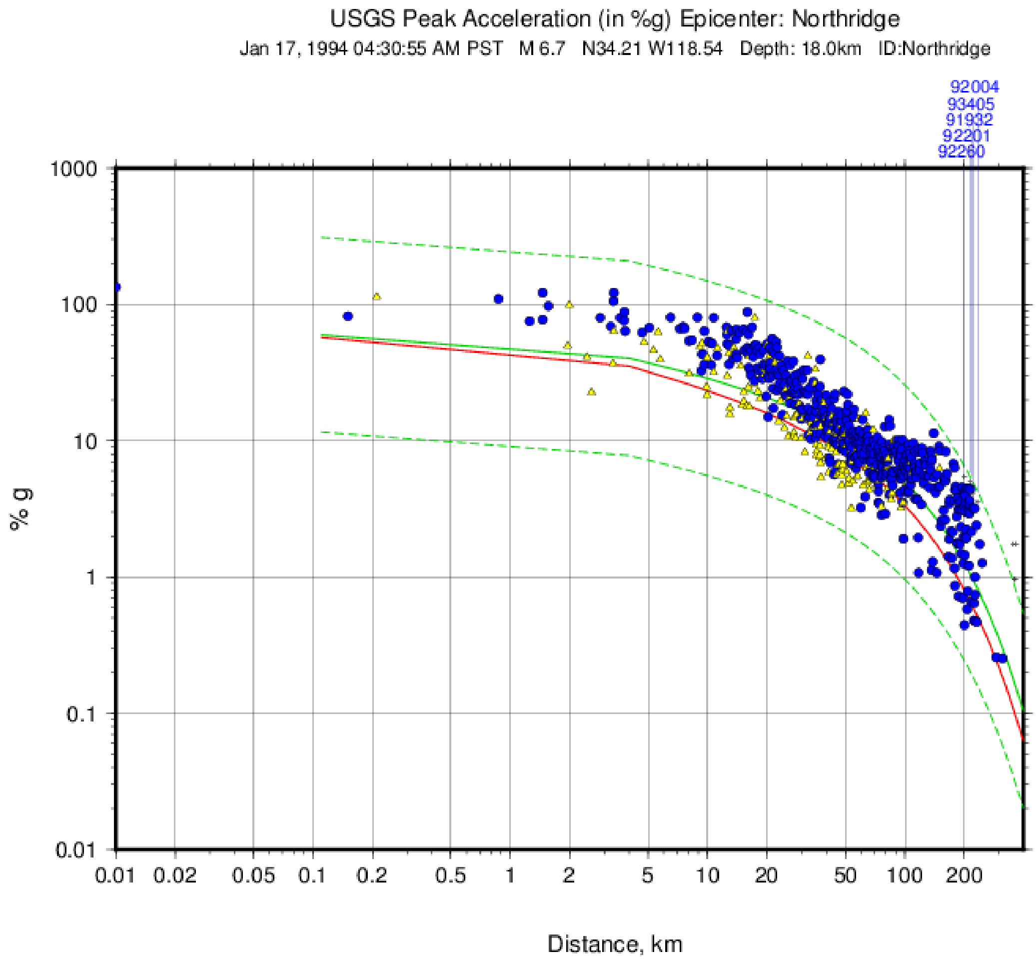


Fig. 3.10: Plot showing the 1994 M6.7 Northridge, CA earthquake PGA data (seismic stations are yellow triangles; DYFI observations are blue circles) plotted with the unbiased (red line) and biased (green line) GMPE. The dashed green lines show the biased GMPE ±3 standard deviations.

plain text (*grid.xml*) and compressed as a zip file (*grid.xml.zip*). As XML, the grid is meant to be self-describing; however, we describe the format here for the sake of completeness.

After the XML header, the first line is the *shakemap_grid* tag:

```
<shakemap_grid xsi:schemaLocation="http://earthquake.usgs.gov
 http://earthquake.usgs.gov/eqcenter/shakemap/xml/schemas/shakemap.xsd"
 event_id="19940117123055" shakemap_id="19940117123055" shakemap_version="2"
 code_version="3.5.1446" process_timestamp="2015-10-30T20:38:19Z"
 shakemap_originator="us" map_status="RELEASED" shakemap_event_type="ACTUAL">
```

Aside from schema information, the *shakemap_grid* tag provides the following attributes:

- *event_id*: Typically this is a string of numbers and/or letters with or without a network ID prefix (e.g., “us100003ywp”), though in the case of major historic earthquakes, scenarios, or other special cases it may be a descriptive string (for example, we have previously used the 1994 Northridge earthquake as an example, and its event_id is “Northridge”).
- *shakemap_id*: Currently the same as *event_id*, above.
- *shakemap_version*: The version of this map, incremented each time a map is revised or reprocessed and transferred.
- *code_version*: The version of the ShakeMap software used to make the map.
- *process_timestamp*: The date and time the event was processed.
- *shakemap_originator*: The network code of the center that produced the map.
- *map_status*: Currently always the string “RELEASED”, but other strings may be used in the future.
- *shakemap_event_type*: Either “ACTUAL” (for real earthquakes) or “SCENARIO” (for scenarios).

The next tag describes the earthquake source:

```
<event event_id="Northridge" magnitude="6.7" depth="18" lat="34.213000"
 lon="-118.535700" event_timestamp="1994-01-17T12:30:55GMT" event_network="ci"
 event_description="Northridge" />
```

Most of the attributes are self-explanatory:

- *event_id*: See above.
- *magnitude*: The earthquake magnitude.
- *depth*: The depth (in km) of the earthquake hypocenter.
- *lat/lon*: The latitude and longitude of the earthquake epicenter.
- *event_timestamp*: The date and time of the earthquake.
- *event_network*: The authoritative seismic network in which the earthquake occurred.
- *event_description*: A string containing the earthquake name or a location string (e.g., “13 km SW of Newhall, CA”).

Following the event tag is the grid_specification tag:

```
<grid_specification lon_min="-119.785700" lat_min="33.379666" lon_max="-117.285700"
 lat_max="35.046334" nominal_lon_spacing="0.008333" nominal_lat_spacing="0.008333"
 nlon="301" nlat="201" />
```

The attributes are:

- *lon_min/lon_max*: The boundaries of the grid in longitude.

- *lat_min/lat_max*: The boundaries of the grid in latitude.
- *nominal_lon_spacing*: The expected grid interval in longitude within the resolution of the numeric format of the output.
- *nominal_lat_spacing*: The expected grid interval in latitude within the resolution of the numeric format of the output.
- *nlon/nlat*: The number of grid points in longitude and latitude. The grid data table will contain nlon times nlat rows.

Following the *grid_specification* tag will be a set of event-specific uncertainty tags:

```
<event_specific_uncertainty name="pga" value="0.466260" numsta="598" />
<event_specific_uncertainty name="pgv" value="0.464209" numsta="595" />
<event_specific_uncertainty name="mi" value="0.624327" numsta="598" />
<event_specific_uncertainty name="psa03" value="0.436803" numsta="594" />
<event_specific_uncertainty name="psa10" value="0.534212" numsta="595" />
<event_specific_uncertainty name="psa30" value="0.577897" numsta="594" />
```

These tags provide the uncertainty for the ground motion parameters (natural log units for all but intensity, which is in linear units) computed as a misfit from the biased GMPE (IPE). This is equivalent to the intra-event uncertainty. The number of stations contributing to each uncertainty is also provided. If the number of stations falls below the minimum required to compute the bias, the uncertainty value will be set to -1.

These lines are followed by a number of grid_field tags:

```
<grid_field index="1" name="LON" units="dd" />
<grid_field index="2" name="LAT" units="dd" />
<grid_field index="3" name="PGA" units="pctg" />
<grid_field index="4" name="PGV" units="cms" />
<grid_field index="5" name="MMI" units="intensity" />
<grid_field index="6" name="PSA03" units="pctg" />
<grid_field index="7" name="PSA10" units="pctg" />
<grid_field index="8" name="PSA30" units="pctg" />
<grid_field index="9" name="STDPGA" units="ln(pctg)" />
<grid_field index="10" name="URAT" units="" />
<grid_field index="11" name="SVEL" units="ms" />
```

Each tag specifies a column in the grid table that follows.

- *index*: The column number where the specified parameter may be found. The first column is column “1.”
- *name*: Description of the parameter in the given column.
- *LON*: Longitude of the grid location (the “site”).
- *LAT*: Latitude of the site.
- *PGA*: Peak ground acceleration at the site.
- *PGV*: Peak ground velocity.
- *MMI*: Seismic intensity.
- *PSA03*: 0.3 sec pseudo-spectral acceleration.
- *PSA10*: 1.0 sec pseudo-spectral acceleration.
- *PSA30*: 3.0 sec pseudo-spectral acceleration.
- *STDPGA*: The standard error of PGA at the site (in natural log units).
- *URAT*: The uncertainty ratio. The ratio STDPGA to the nominal standard error of the GMPE at the site (no units).

- *SVEL*: The 30-meter shear wave velocity (Vs30) at the site.

The measurement units:

- *dd*: Decimal degrees.
- *pctg*: Percent-g (i.e., nominal Earth gravity).
- *cms*: Centimeters per second.
- *intensity*: Generally Modified Mercalli Intensity, but potentially other intensity measures.
- *ms*: Meters per second.
- *ln(pctg)*: Natural log of percent-g.
- *ln(cms)*: Natural log of centimeters per second.

The number of *grid_field* tags will vary: smaller-magnitude earthquakes may not have the pseudo-spectral acceleration values; scenarios will not have STDPGA or URAT; and maps that have not been site corrected will not have SVEL.

The *grid_field* tags are followed by the *grid_data* tag, the gridded data, and the closing tags:

```
<grid_data>
-119.7857 35.0463 4.3 4.21 5.26 5.76 5.76 1.09 0.5 1 800
-119.7774 35.0463 4.34 4.23 5.27 5.8 5.78 1.1 0.5 1 800
-119.7690 35.0463 4.37 4.25 5.27 5.84 5.81 1.1 0.5 1 800
...
</grid_data>
</shakemap_grid>
```

The fast index for the coordinates is longitude, the slow index is latitude. Dimensions are from upper left to lower right (i.e., from longitude minimum/latitude maximum to longitude maximum/latitude minimum). The GMT program *xyz2grd* (coupled with *gmtconvert*) is particularly useful for converting the *grid.xml* data into a usable grid file.

Rock Grid XML. The file *rock_grid.xml.zip* is a zipped XML file containing the interpolated grid without site amplifications applied. The rock grid has the same structure as *grid.xml*, but Vs30 values and PGA uncertainty values are not supplied. *Amplify Ground Motions* in the *Technical Guide*.

Uncertainty Grid XML. The file *uncertainty.xml.zip* is a zipped XML file containing the standard errors for each of the ground-motion parameters at each point in the output grid. It has the same structure as *grid.xml*, with the additional *grid_field* names:

- *STDPGA*: Standard error of peak ground acceleration.
- *STDPGV*: Standard error of peak ground velocity.
- *STDMMI*: Standard error of seismic intensity.
- *STDPSA03*: Standard error of 0.3 sec pseudo-spectral acceleration.
- *STDPSA10*: Standard error of 1.0 sec pseudo-spectral acceleration.
- *STDPSA30*: Standard error of 3.0 sec pseudo-spectral acceleration.

The standard errors are given in natural log units, except for intensity (linear units). The PSA entries will be available only if the PSA ground motion parameters were mapped (typically only for earthquakes of M >= 5.0). No ground motion data or Vs30 values are available in *uncertainty.xml.zip*; for those, use *grid.xml.zip*.

Grid XYZ. *grid.xyz* is a plain-text comma-separated file of gridded ground motions.

Note: The use of *grid.xyz* is deprecated. It is difficult to maintain and have it remain backward-compatible. All users are urged to use the XML grids instead, and to switch to the XML grids if they are using *grid.xyz*. *grid.xyz* will disappear in a future ShakeMap release.

Station Lists

As discussed in the section *Input Files*, ShakeMap produces station lists of input data in XML and text format. We also produce a version in GeoJSON format, which is available for download, and is used by the website to plot the stations on the interactive maps. The station data is available for viewing online by selecting the "Station List" tab on an event's ShakeMap page. See Figure 3.11 for an example.

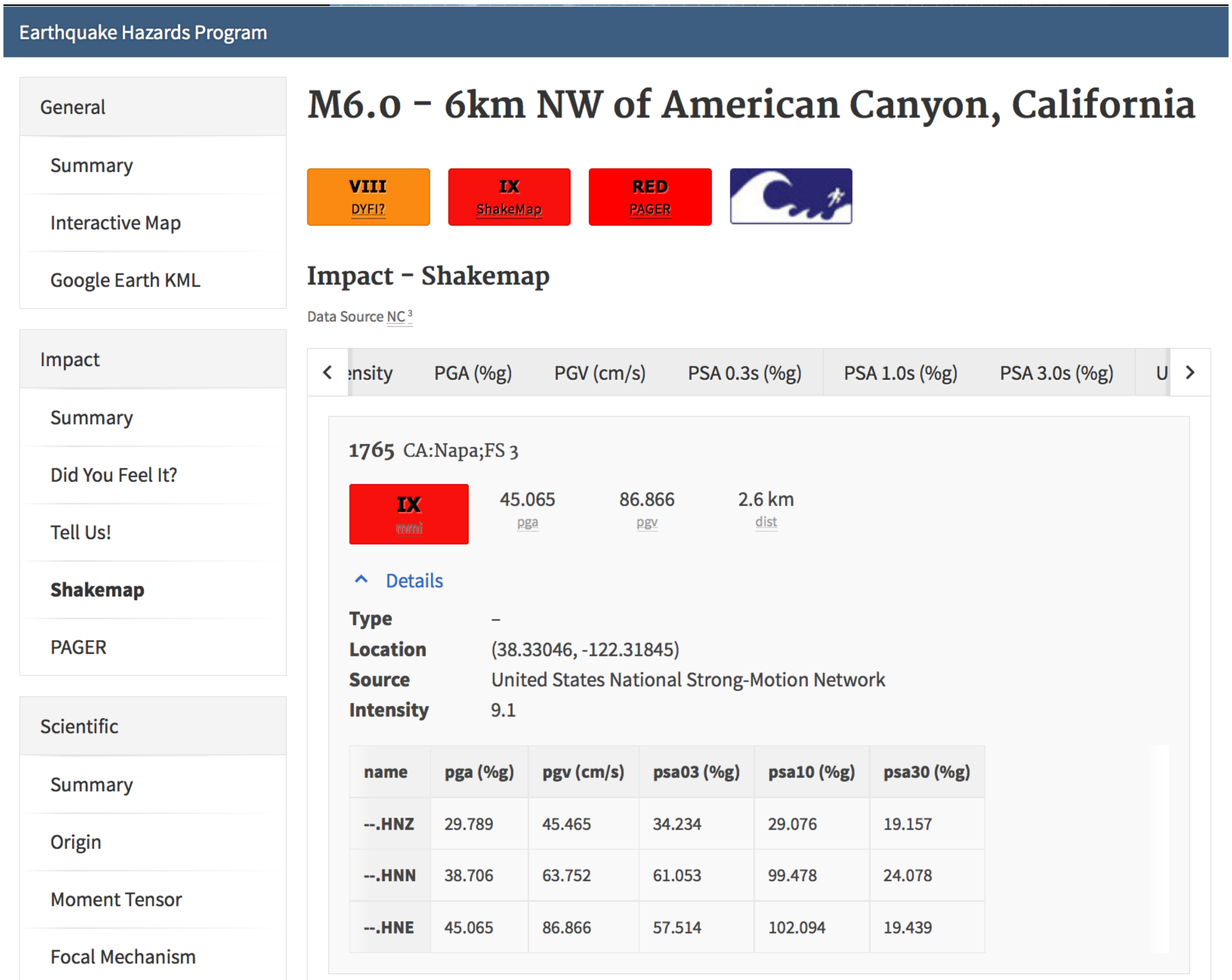


Fig. 3.11: Station table view from ShakeMap event-specific webpages. Link is at right of tabs above the map (see Figure 3.1).

GIS Products

ShakeMap GIS Files (zipped) are a collection of shapefiles of polygons of the ShakeMap model outputs for each shaking metric: MMI, PGA, PGV, and PSA at three periods (0.3, 1.0, and 3.0 sec). These file should be easily importable into a GIS system. The ESRI Raster Files (also zipped) are a collection of ESRI-formatted binary files. It should be relatively easy to convert these to (for example) ArcGIS grids using the standard tools provided with the software. The contours are useful primarily for overlaying with other data for visualization purposes.

The file base names in each archive are abbreviations of the type of ground-motion parameter:

mi	macroseismic intensity (usually, but not necessarily, mmi)
pga	peak ground acceleration
pgv	peak ground velocity
psa03	0.3 s pseudo-spectral acceleration
psa10	1.0 s pseudo-spectral acceleration
psa30	3.0 s pseudo-spectral acceleration

The sub-sections that follow describe available file and product types.

Shapefiles

GIS shapefiles are comprised of four or five standard associated GIS files:

.dbf	database file with layer attributes
.shp	the file with geographic coordinates
.shx	an index file
.prj	contains projection information
.lyr	contains presentation properties (only available for PGA, PGV, and MMI)

In this application, the shapefiles are contour polygons of the peak ground-motion amplitudes in ArcView shapefiles. These contour polygons are actually equal-valued donut-like polygons that sample the contour map at fine enough intervals to accurately represent the surface function. We generate the shapefiles independent of a GIS using a shareware package (*shapelib.c*). Contouring, as well as polygon formation and nesting, is performed by a program written in the *C* programming language by Bruce Worden, and is included in the ShakeMap software distribution.

GIS Shapefiles. Contour polygons for the PGM parameters are available as shapefiles intended for use with any GIS software that can read ArcView shapefiles. Note, however, that the peak ground velocity (PGV) contours are in cm/s, and are therefore **not** suitable for HAZUS input.

The contour intervals are 0.04g for PGA and the three PSA parameters, and 2cm/s for PGV. The file also includes MMI contour polygons in intervals of 0.2 intensity units. These shapefiles have the same units as the online ShakeMaps. The archive of files is compressed in zip format and called *shape.zip*. The *shape.zip* file is available for all events, but the spectral values are generally only included for earthquakes of magnitude 4.0 and larger. **HAZUS'99 Shapefiles and HAZUS-MH Geodatabases**. We generate shapefiles that are designed with contour polygons intervals that are appropriate for use with the Federal Emergency Management Agency's (FEMA) HAZUS-MH® software, though they may be imported into any GIS package that can read ArcView shapefiles. Because HAZUS software requires PGV in inches/sec, this file is not suitable for all applications. The contour intervals are 0.04g for PGA and the two PSA parameters (HAZUS only uses 0.3 and 1.0 sec periods), and 4 inches/sec for PGV.

HAZUS'99 users can use the *hazus.zip* shapefiles (see below) directly. However, the 2004 release of HAZUS-MH uses geodatabases, not shapefiles. As of this writing, FEMA has a temporary fix in the form of Visual Basic script that imports ShakeMap shape files and exports geodatabases. FEMA has plans to incorporate such a tool directly into HAZUS-MH in the next official release (D. Baush, FEMA, Region VIII, oral commun., 2015).

HAZUS traditionally used the epicenter and magnitude of an earthquake as reported, and used empirical relationships to estimate ground motions over the affected area. These simplified ground-motion estimates would drive the computation of losses to structures and infrastructure, estimates of casualties and displaced households (for more details, see *NIBS, 1997*). With the improvements to seismic systems nationally, particularly in digital strong-motion data acquisition, and the advent of ShakeMap, HAZUS can now directly import a much more accurate description of ground shaking. The improved accuracy of the input to loss-estimation routines can dramatically reduce the uncertainty in loss estimation due to poorly constrained shaking approximations.

The HAZUS GIS files are only generated for events that are larger than (typically) magnitude 4.5. The set of shapefiles for these parameters is an archive of files compressed in zip format (*hazus.zip*) to facilitate file transfer.

Note: An important note on the values of the parameters in the HAZUS shape files is that they are empirically corrected from the standard ShakeMap **peak ground motion values** to approximate the **geometric mean** values used for HAZUS loss estimation. HAZUS was calibrated to work with mean ground motion values (FEMA, 1997). Peak amplitudes are corrected by scaling values down by 15 percent (Campbell, 1997; Joyner, oral commun., 2000). While more recent work by *Beyer and Bommer (2006)* suggests different conversion factors, for the HAZUS shape files we continue to use 15 percent to maintain consistency in HAZUS results. As of this writing, FEMA is considering switching to peak ground motions as presented by ShakeMap rather than employing the geometric mean component.

ESRI Raster Files (*.fit* files)

ESRI raster grids of the ground-motion parameters and their uncertainties are also available. The files are found in a zipped archive called *raster.zip*. Each archive contains four files per parameter: *<param>.fit* and *<param>.hdr*, which contain the ground-motion data, and *<param>_std.fit* and *<param>_std.hdr*, which contain the uncertainties for the ground motions. See *grid.xml* for information on units. As with the other GIS files, PGA, PGV, and MMI are available for all events, while the PSA parameters are usually only included for earthquakes M4.5 and larger.

Loading ESRI Raster Grid ShakeMaps into ArcGIS

1. Open the ArcToolbox in ArcMap
2. Select Multidimension Tools -> Make NetCDF Raster Layer
3. In the dialog that appears, select the input *.grd* file you downloaded and unzipped, and name the layer appropriately ("vs30", etc.)
4. The new layer should appear in your list of layers.
5. Note: This layer is ephemeral—if you want to keep the raster version of the data, you'll have to save the layer to a file.

Google Earth Overlay

The file *<event_id>.kmz* enables the user to view the ShakeMap in Google Earth (or other KML-compliant applications). A color-scaled intensity overlay is provided along with a complete station list, contours and polygons of intensity and peak ground motion, a fault representation (if provided), epicenter indicator, intensity scale, and the USGS logo. The transparency of the intensity overlay is adjustable by the user, as is the appearance of seismic stations. The KMZ file embeds several other files that may be found in the event's download directory:

```
epicenter.kmz
fault.kmz
overlay.kmz (links to ii_overlay.png)
stations.kmz
contours.kmz
```

Note that the KMZ file is static and will not automatically update when we update the ShakeMap for an event, so periodic checks for updated maps and reloading of the KMZ is recommended.

In addition to the ShakeMap-produced KMZ file, the USGS produces a KML file (linked near the top of the page in the event-centric pages with the title "Google Earth KML") which contains not only ShakeMap data, but also data from PAGER, DYFI, and other sources. This file should be the preferred source, as it will have the most-up-to-date links, though it does not have all of the layers available in the ShakeMap KMZ file.

Contour Files

As mentioned above in the ShakeMap Output GIS format section, contour files are available for general GIS, HAZUS, and KML formats. We also provide GeoJSON format contours, all under the ShakeMap event-specific "Downloads" tab.

3.2.3 Real-Time Product Distribution, Automatic Access, and Feeds

ShakeMap products are distributed by a number of means immediately after they are produced. The intent of these products is to help responders and other responsible parties effectively manage their post-earthquake activities, so we make it as easy as possible for users with a variety of technological sophistication and infrastructure to access them. The general distribution methods are interactive Web downloads, RSS feeds, GeoJSON feeds, ShakeCast, the Product Distribution Layer (PDL) client, and GIS web mapping services.

Interactive Web Downloads

The easiest way to obtain ShakeMap products immediately following an earthquake is from the ShakeMap or USGS Earthquake Program webpages. The event page for any given earthquake has a download link where all of the products for that event may be found. The ShakeMap page for an event also has a download link that lists just the ShakeMap products. The variety of formats for ShakeMap are described in the previous section.

RSS Feeds

USGS Earthquake Program earthquake information Feeds currently include Really Simple Syndication (RSS) feeds. However, the RSS feeds are deprecated; they will be decommissioned in 2016.

GeoJSON Feeds

Automatically Retrieving Earthquake Data and ShakeMap Files. The USGS Earthquake Program GeoJSON feed provides USGS ShakeMap, along with most other USGS real-time earthquake products. GeoJSON is an extension of the JavaScript Object Notation (JSON) standard and allows for a variety of geospatial data structures. There are JSON parsers in most modern languages, including Python, Perl, Matlab, and R.

In order to automatically ingest the above data, use the automated GeoJSON feeds. Mike Hearne (USGS), provides an example python script for querying the USGS Magnitude 2.5+ thirty-day GeoJSON feed, and downloading the most recent version of the event products desired by the user. In addition, the USGS Haz-Dev group provides other scripts in various programming languages that allow access to the GeoJSON feeds. Modifications to these scripts allow access to any ShakeMap (or other) products automatically, GIS flavors included.

Example. *How can I use your API to get ShakeMap files download for specific events (that shook Guatemala)?*

The following GeoJSON summary query includes events between 2015-01-01 and 2016-01-01 in the bounding box lat. 10 to 20, long. -95 to -85, in case an event outside Guatemala results in shaking inside Guatemala; and includes a ShakeMap product:

```
http://earthquake.usgs.gov/fdsnws/event/1/query?format=geojson&
starttime=2015-01-01T00:00:00&maxlatitude=20&minlatitude=10&maxlongitude=-85&
minlongitude=-95&endtime=2016-01-01T00:00:00&producttype=shakemap
```

The results include an array of features with summary information for each event. The *detail* property is a URL for the GeoJSON detail feed that includes URLs for ShakeMap files. For example, for the *us100044xh* event, the GeoJSON detailed feed URL is:

```
HTTP://earthquake.usgs.gov/fdsnws/event/1/query?eventid=us100044xh&format=geojson
```

The URLs for the ShakeMap files can be found inside the feed:

```
FEED.properties.products.shakemap[0].contents['download/grid.xml.zip'].url
FEED.properties.products.shakemap[0].contents['download/shape.zip'].url
```

In this case, these are the specific URLs are for the *grid.xml* file and for the *shape.zip* files, respectively:

```
http://earthquake.usgs.gov/archive/product/shakemap/us100044xh/us/1450404175265/
download/grid.xml.zip
http://earthquake.usgs.gov/archive/product/shakemap/us100044xh/us/1450404175265/
 download/shape.zip
```

Additional Feeds

More information about USGS earthquake data feeds is available at our Feeds & Notifications page.

ShakeCast System

ShakeCast delivers user-specified ShakeMap products to the user's local or virtual system(s), and runs fragility-based damage (or inspection priority) calculations for specific portfolios. More advanced features of ShakeCast include a complete suite of damage estimation and mapping tools, coupled with sophisticated tools to notify responsible parties within an organization on a per-facility basis. See *Related Systems* for more details. Complete background on ShakeCast can be found on the ShakeCast homepage and Wiki and the documentation provided therein.

Product Delivery Layer (PDL) Client

Finally, for academic and government users, ShakeMap products (and other earthquake products) are communicated through the USGS's Product Distribution Layer (PDL).

Web Mapping (GIS) Services

In addition to the downloadable GIS-formatted ShakeMaps (including shapefiles) that are readily available for each ShakeMap event, USGS also hosts a real-time 30-day Signficant 'Earthquake GIS ShakeMap Feed. ESRI provides a separate Disaster Response ArcGIS service, providing live feeds to several USGS post-earthquake products.

Related GIS Service Interactions

Users can access the ShakeMap data behind the GIS service in a variety of ways via the ArcGIS Server "REST API". Some examples of commonly used data-access options are detailed below.

- Export Map Image: Download a static image of the map to include in their work.
- Identify: Retrieve service data for given geographic location. (Point, Line, Polygon or Envelop)
- Find: Query service data that contains certain attributes. (ex. ShakeMap data for distinct event id)
- Query: Query a specific layer in a service and return a detailed featureset.

Along with the common GIS service interactions listed above, there are many other calls that GIS developers can make through the REST API.

Note: Earthquake Significance. The NEIC associates a *significance* number with each earthquake event. Larger numbers indicate more significance. This value is determined by a number of factors, including magnitude, maximum MMI, felt reports, and estimated impact. The significance number ranges from 0 to 1000. The "30 day significant earthquake feed” that determines which events are included in the ShakeMap GIS feed uses events with a significance of 600 and greater.

Accessing ShakeMap GIS Files: While this GIS service only provides access to significant earthquakes that have occurred within the last thirty days, users can download GIS files for significant events on our website after the thirty-day period. The significant earthquake archive has a list of large events with links to each event’s webpage. From the event page, users can click on the ShakeMap tab and navigate to the “Downloads” section to get a zipped bundle of shapefiles.

Acknowledgement: USGS appreciates guidance from the Esri Aggregated Live Feed team, specifically Derrick Burke and Paul Dodd. Their willingness to share best practices for robust real-time sharing of GIS data enabled this project to be completed.

3.3 ShakeMap Archives

All ShakeMaps are available for viewing and download online. The ShakeMap Archives consist of three primary repositories: **Recent ShakeMaps**, the **ShakeMap Atlas** for historic earthquakes (primarily 1970-2012), and a collection of hypothetical earthquake **ShakeMap Scenarios**. For example, scenario earthquakes compiled for Northern and Southern California represent over 200 different earthquake ruptures studied for California, as detailed below. Formats for all ShakeMaps, whether near–real-time, historic, or future scenarios, are uniform.

Note: Some older archival ShakeMaps online were generated with earlier versions of the ShakeMap software; hence, they do not contain up-to-date formats and all products. This will be remedied as older events are rerun and updated. One can tell from the *processed time* on the bottom of any ShakeMap when it was run.

3.3.1 Real-time ShakeMaps

In the U.S., ShakeMaps are generated via independent systems running at ANSS Regional Seismic Systems (RSNs) in Northern California, Southern California, the Pacific Northwest, Utah, Nevada, and Alaska. For the rest of the U.S., the ShakeMap group at the USGS National Earthquake Information Center (NEIC) in Golden, Colorado produces maps for the regional networks operating in Hawaii, New England, and the Central and Eastern U.S. on a system referred to as Global ShakeMap (GSM). The input, metadata, and output files produced by all these instances are aggregated by the USGS via the Earthquake Hazards Program web system. GSM also provides backup capabilities for the RSNs, but with degraded capabilities; not all data are flowing from the RSNs to GSM automatically.

Separate independent systems running in Puerto Rico and New England generate ShakeMaps, but these instances do not deliver them through the USGS Earthquake Hazards Program webpages (at the time of this writing). GSM covers these regions but does not yet access the full set of data available to these regional systems. For more information on the ANSS regional and the national ShakeMap system implementations and operations, see the section on *Regional Operations*.

Internationally, USGS ShakeMap is installed and operational in Italy, France, Portugal, Switzerland, Romania, Indonesia, Iran, Iceland, Panama, and several other nations (see Figure 3.12). Several instances of ShakeMap are in testing or operational mode in the Middle East (including Oman, Morocco, and the U.A.E.; M. Franke, written comm., 2015). In addition, other ShakeMap installations are in testing in Latin America and the Caribbean (Chile, Costa Rica, Colombia, Mexico, Costa Rica), and in Southeast Asia (Malaysia and Korea). Discussions have taken place with several other interested countries.

Note: Very impressive systems analogous to ShakeMap operate in Japan (JMA), Taiwan, China, New Zealand, Turkey, and several other countries.

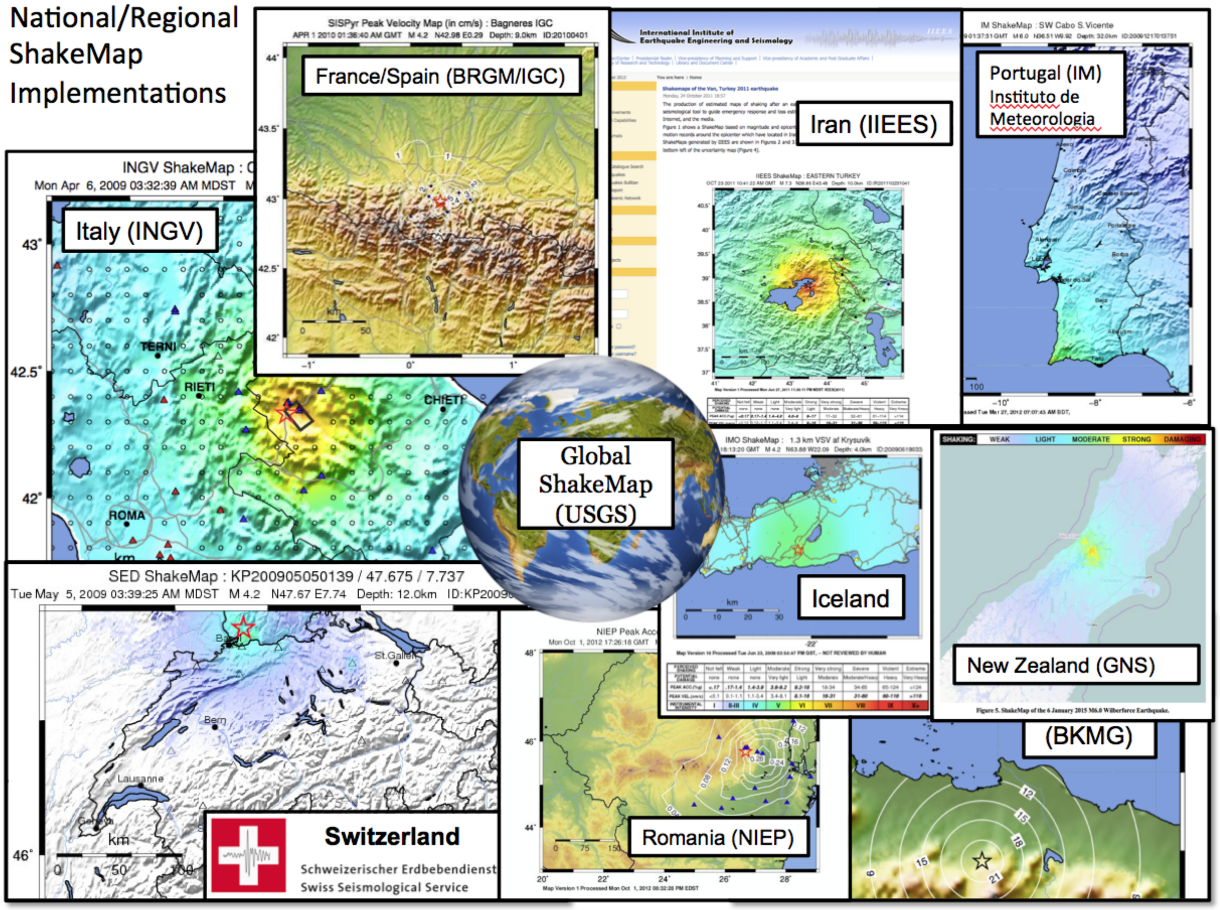


Fig. 3.12: International ShakeMap Systems

3.3.2 ShakeMap Atlas

ShakeMap was designed with near–real-time earthquake response purposes in mind. However, many of the strategies for mapping the patterns of peak ground motions for real-time applications described above prove useful for re-creating the shaking from historic earthquakes.

The ShakeMap Atlas (*Allen et al., 2008*, *2009a*) is a self-consistent, well-calibrated collection of historic earthquakes for which ShakeMaps were systematically generated. The Atlas constitutes an invaluable online resource for investigating near-source strong ground motion, as well as for seismic hazard, scenario, risk, and loss-model development.

Finding Atlas ShakeMaps Online

- **Atlas Version 1.0** (*Allen et al., 2008*) ShakeMaps are available online on the ShakeMap homepage, which consists of all the standardized ShakeMap products and formats. Output grids for the entire dataset can also be obtained at that site.
- **Atlas Version 2.0** (*Garcia et al. (2012a)* ShakeMaps are available by searching the USGS Comprehensive Catalogue (ComCat) Earthquake database. Be sure to select "ShakeMap Atlas" as the "Contributor" from the "Advanced Options" dropdown menu.

The original (2009) Atlas is a compilation of nearly 5,000 ShakeMaps for the most significant global earthquakes between 1973 and 2007 (*Allen et al., 2008*). *Garcia et al. (2012a)* introduced an update of the Atlas, which extends the time period through 2012, with a total of 6,100 events. The revised Atlas 2.0 includes: a new version of the ShakeMap software (V3.5) which improves interpolation and uncertainty estimations; an updated earthquake source catalogue that includes regional locations and finite fault models; a refined strategy to select prediction and conversion equations based on a new seismotectonic regionalization scheme (*Garcia et al., 2012b*); and vastly more macroseismic-intensity and ground-motion data from international agencies.

In order to best replicate shaking that occurred during historic and recent earthquakes, we employ many of the ShakeMap tools described in the previous sections. For many older events, the important constraints (in addition to the usual site condition map) are the fault rupture geometry, macroseismic intensity, and peak ground motion data. As previously described, combining peak ground motions and macroseismic data was accomplished seamlessly and rigorously with the new interpolation scheme developed by *Worden et al. (2010)*. This strategy was in part aimed at most accurately representing historic earthquake shaking maps, which are often constrained predominantly by key macroseismic observations, and is essential for the Atlas.

The Atlas provides a hazard base layer for an number of systems that require estimates of the shaking values where losses occurred. To this end, the Atlas is used for the Earthquake Consequences Database within the Global Earthquake Model initiative (GEMECD; *So, 2014*). The "GEMECD subset" is a collection of approximately 100 events which constitute the most important and damaging events since about 1973. The purpose of the GEMECD subset is to provide the Global Earthquake Model (GEM) Foundation—and hence the wider earthquake hazard and loss community—a common-denominator hazard layer for calibrating and testing earthquake damage and loss models. The Atlas is also the calibration hazard layer for the USGS PAGER system (e.g., *Wald et al., 2008*; *Jaiswal and Wald, 2010*; *Pomonis and So, 2011*).

A subset of the Atlas was also employed by *Zhu et al. (2014)* for the calibration of near–real-time liquefaction probability maps, and by *Nowicki et al. (2014)* for near–real-time landslide mapping. As with earlier studies (including *Godt et al., 2008*; *Jaiswal et al., 2010*, *2012*; *Knudsen and Bott, 2011*; *Matsuoka et al, 2015*), these authors recognized the importance of calibrating empirical ground failure and loss models against a standardized set of uniformly-produced shaking hazard maps so as to allow comparison of models based on consistent hazard inputs. Figure 3.14 shows an example of the possibility of constraining shaking at landslide sites using ShakeMap layers for the 2008 M7.9 Wenchuan, China earthquake, employing shaking constraints provided by strong-motion and intensity data as well as detailed fault geometry.

3.3.3 ShakeMap Scenarios

In addition to historical and near–real-time applications, ShakeMap has become widely used for earthquake mitigation and planning exercises through earthquake scenarios. A scenario represents one realization of a potential future earthquake by assuming a particular magnitude, location, and fault-rupture geometry and estimating shaking using a variety of strategies (including ShakeMap with GMPEs). Some of the technical issues related to scenario generation are discussed in the *Technical Guide*. Here we cover the many uses for earthquake scenarios from the users' perspective.

In planning and coordinating emergency response, utilities, local government, and other organizations are best served by conducting training exercises based on realistic earthquake situations—ones similar to those they are most likely

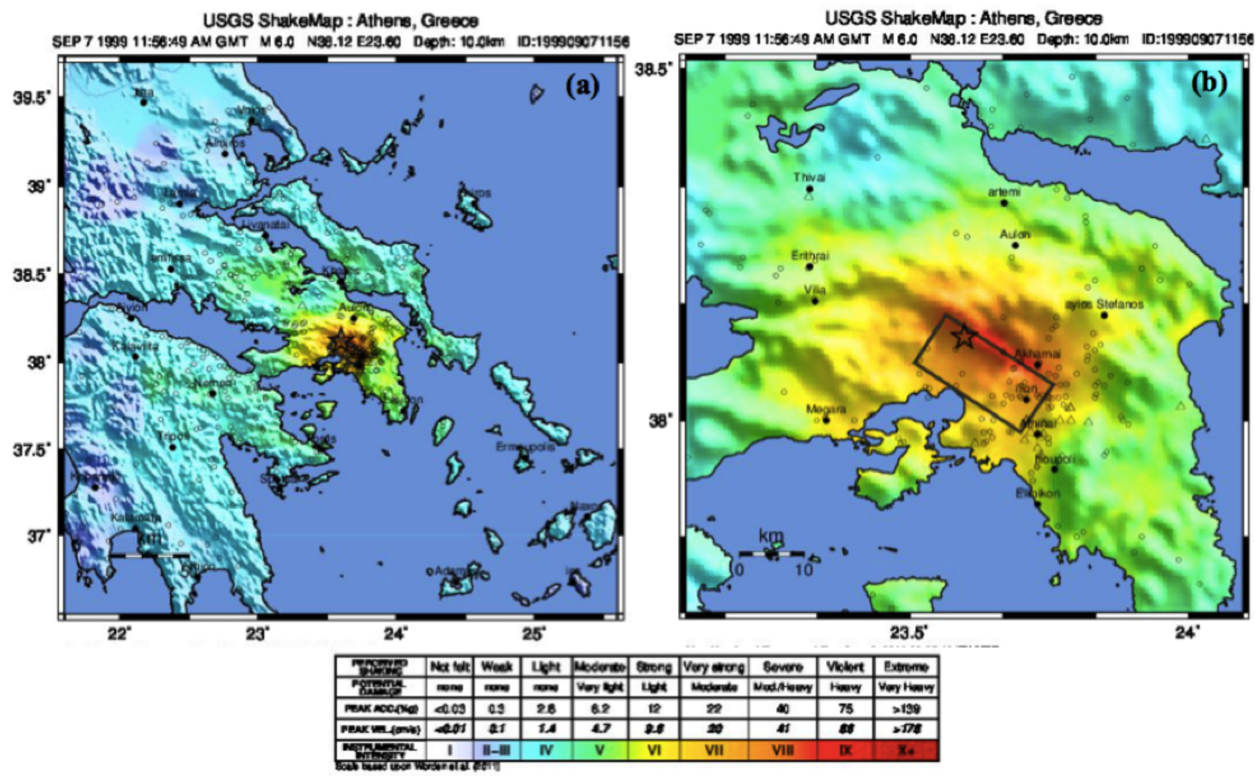


Fig. 3.13: Example of the macroseismic intensity ShakeMaps for one ShakeMap Atlas event: the 1999 M6.0 Athens, Greece earthquake. (A) overview map; and (B) zoomed map. The black rectangle delineates the surface projection of the finite fault (a normal fault dipping southwest). Circles represent native MMI data; triangles show PGM data converted to MMI values via the *Worden et al. (2012)* GMICE, the choice of which automatically redefines the legend scale. After *Garcia et al. (2012a)*.

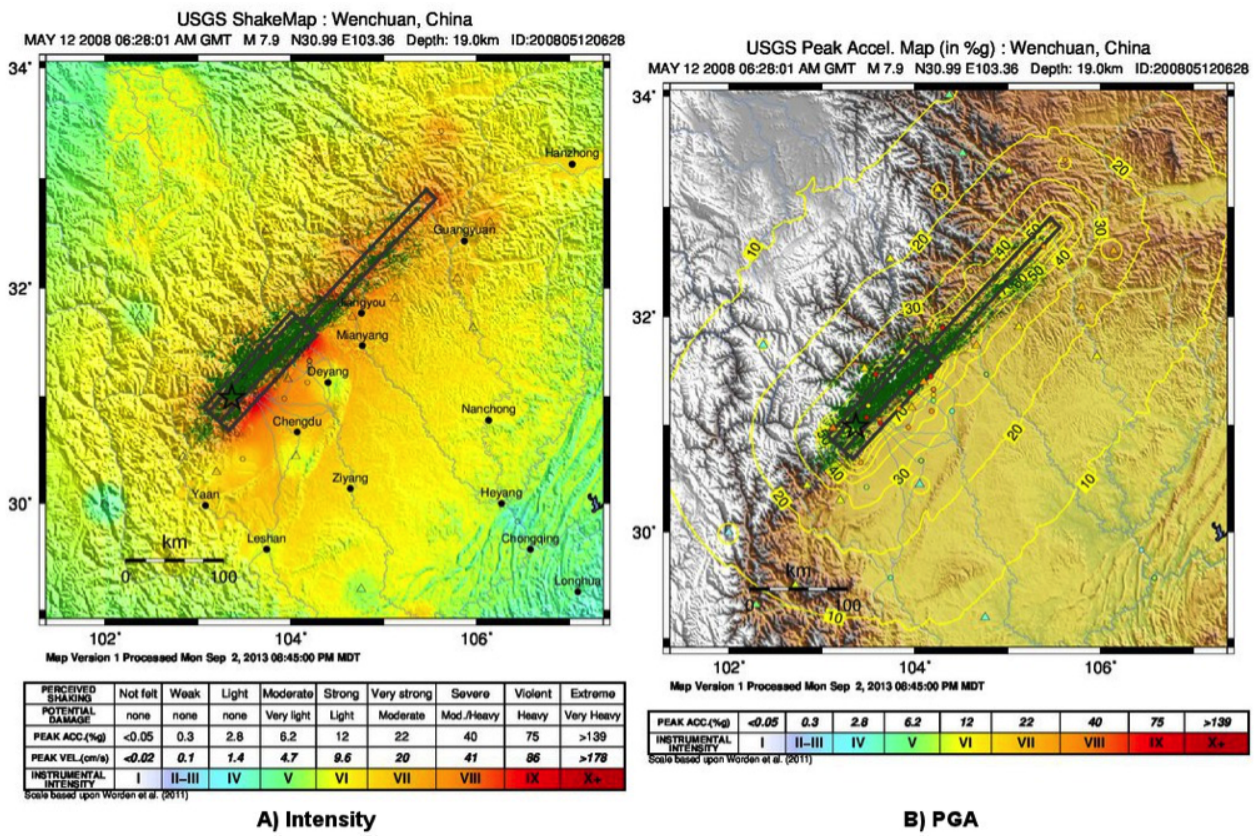


Fig. 3.14: Example of the ShakeMaps for the 2008 M 7.9 Wenchuan, China earthquake for (A) Intensity and (B) PGA. Green polygons show areas of landsliding mapped out by *Dai et al. (2010)*. Black rectangles delineate the surface projection of the different fault segments involved in the rupture. Triangles indicate native strong motion stations; circles represent MMI data converted to GM values via a GMICE (here *Worden et al., (2012)*, the choice of which automatically redefines the legend scale.

to face. ShakeMap Scenario earthquakes can fill this role. They can also be used to examine exposure of structures, lifelines, utilities, and transportation corridors to specified potential earthquakes.

The September, 2015, Report to NEHRP Agencies from the Advisory Committee on Earthquake Hazards Reduction (ACEHR), notes:

> *USGS Recommendation 4 - ACEHR recommends the USGS expand earthquake scenario development in conjunction with stakeholder engagement in order to examine consequences of earthquakes in high-risk urban areas.*

To this end, USGS ShakeMap webpages now display many earthquake scenarios, and we are working to develop a comprehensive suite of scenarios for all at-risk regions of the United States (see *Thompson et al., 2016*).

> *USGS Recommendation 5 - ACEHR recommends the USGS work with operators of critical infrastructure and lifeline systems to define and integrate near real-time earthquake data and other seismic information into system monitoring so that operators can quickly assess system impacts from earthquake movements and take appropriate actions. This development should be linked with the EEW program.*

A ShakeMap earthquake scenario is simply a ShakeMap with an assumed magnitude and location, and, optionally, specified fault geometry. For example, Figure 3.15 shows ShakeMap scenario intensity (top) and peak velocity (bottom) maps for a hypothetical earthquake of M7.05 on the Hayward Fault in the eastern San Francisco Bay area. Due to the proximity to populated regions of Oakland, Berkeley, and surrounding cities, this scenario represents one of the most destructive earthquakes that could impact the region. Different renditions of this particular scenario have been widely used for evaluating the region's capacity to respond to such a disaster among federal, state, utility, business, and local emergency response organizations.

The USGS and ANSS partners receive numerous requests for ShakeMap scenarios annually. The NEIC Global ShakeMap (GSM) operators have also generated scores of scenarios for colleagues, partners, other federal agencies, non-profit organizations, and governments around the globe. These and other scenarios are available online on the ShakeMap webpages. They are formatted the same as other ShakeMaps, so they can be easily used in response planning and loss estimation as well as for educational purposes.

ShakeMap earthquake scenarios can be an integral part of earthquake emergency response planning. Primary users include city, county, state and federal government agencies (e.g., the California EMA, FEMA); and emergency-response planners and managers for utilities, businesses, and other large organizations. ShakeMap scenarios are particularly useful in planning and exercises when combined with loss-estimation systems such as PAGER, HAZUS, and ShakeCast, which provide ShakeMap-based estimates of overall social and economic impact, detailed loss estimates, and inspection priorities, respectively. Since ShakeMap's inception, operators have generated hundreds of earthquake scenarios that have been used in formal earthquake response exercises around the world.

Finding ShakeMap Scenarios Online

- **Scenarios 1.0**. ShakeMaps are available online on the ShakeMap homepage, which consists of all the standardized ShakeMap products and formats. Output grids for the entire dataset can also be obtained at that site.
- **Scenarios 2.0**. The Next Generation Scenarios (NGS) will be available by searching the USGS Comprehensive Catalogue (ComCat) Earthquake database. Be sure to select "ShakeMap Scenarios" as the "Contributor" in the "Advanced Options" dropdown menu. The available catalogues of scenarios will change over time.

Generating Earthquake Scenarios

Given a selected event, we have developed tools to make it relatively easy to generate a ShakeMap earthquake scenario. All that is required is to assume a particular fault or fault segment will (or did) rupture over a certain length and with a chosen magnitude, and to generate a file describing the fault geometry and another describing the magnitude and hypocenter of the ostensible earthquake (see the *Software & Implementation Guide* for details). ShakeMap can then

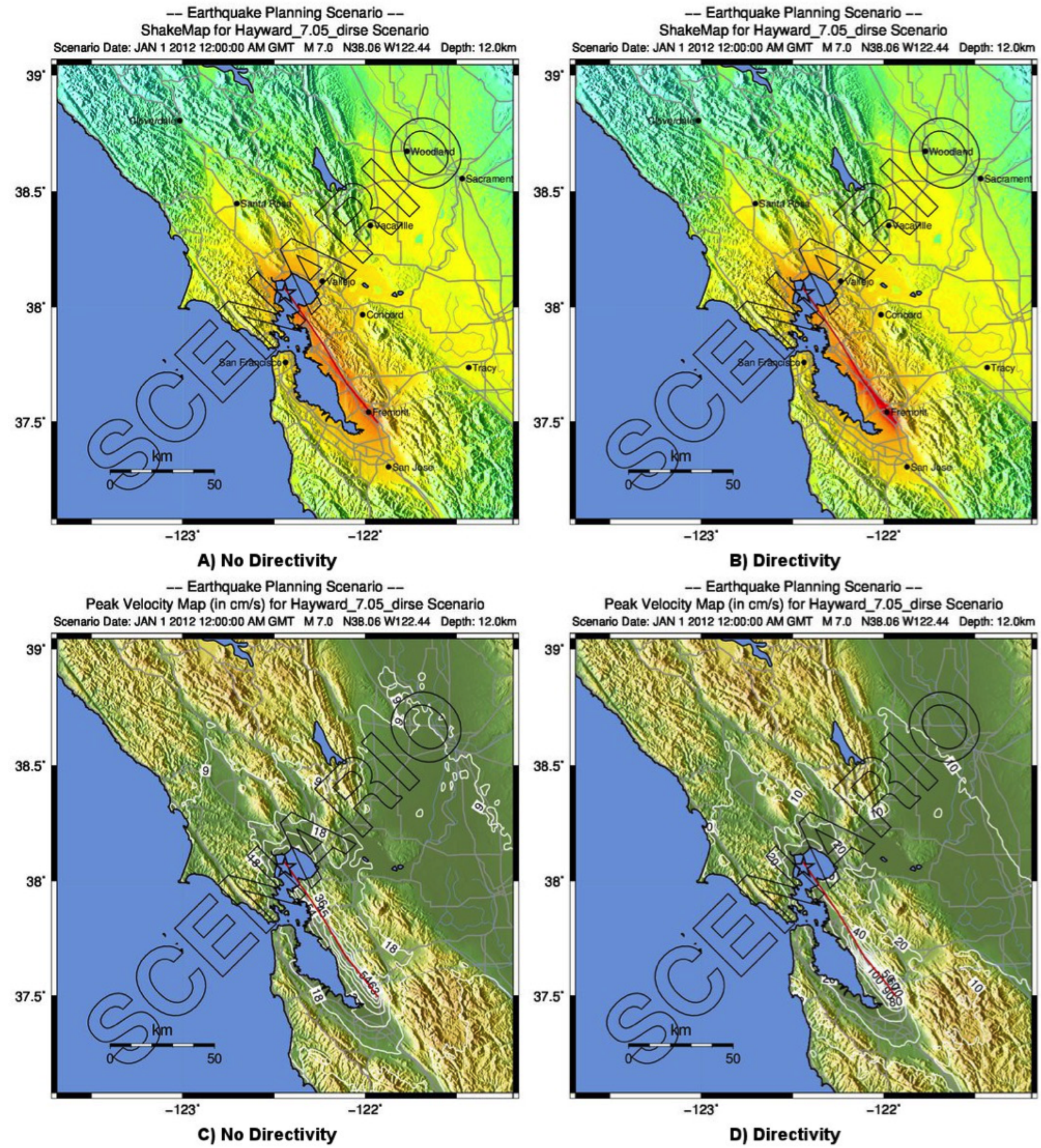


Fig. 3.15: ShakeMap scenario intensity (top) and peak velocity (bottom) maps for a M7.05 Hayward Fault, CA, earthquake: A) intensity; no directivity, B) intensity; directivity added, C) peak velocity; no directivity, and D) peak velocity; directivity added.

estimate the ground shaking at all locations over a chosen area surrounding the fault and produce a full suite of data products just as if the event were a real earthquake. Ground motions are usually estimated using GMPEs to compute peak ground motions on rock conditions; however, the operator may also supply ground-motion estimates from external programs in the form of GMT grid files. As described in *Amplify Ground Motions*, ShakeMap corrects the amplitudes based on the local site soil conditions unless configured otherwise.

At present, ground motions are estimated using empirical attenuation relationships (though we can use gridded ground-motion estimates from other sources for those who wish to provide them). We then correct the amplitudes based on the local site soil conditions (Vs30) as we do in the general ShakeMap interpolation scheme. Fault finiteness is included explicitly, basin depth can be incorporated where appropriate, and source directivity is included via the relationships developed by *Rowshandel (2010)*. Depending on the level of complexity needed for the scenario, event-specific factors, such as variable slip distribution, could also be incorporated in the amplitude estimates fed to ShakeMap.

In most cases, we do not consider the direction of rupture, nor do we modify the peak motions by a directivity term. Fault geometries are specified with a fault file that represents the fault planar segments. With this approach, the location of the earthquake hypocenter does not have any effect on the resulting ground-motions; only the location and dimensions of the fault matter. If we were to add directivity to the calculations, then different choices of hypocentral location could result in significantly different motions for the same magnitude earthquake and fault segment.

Rather, our approach is to generally show the average effect because it is difficult to justify a particular choice of hypocenter or to show the results for every possible hypocentral location. Our empirical predictive approach also only gives median peak–ground-motion values, so it does not account for all the expected variability in motions, only the aforementioned site amplification variations. Actual ground motions show significant variability for a given distance, magnitude, and site condition and, hence, the scenario ground-motions are more uniform than would be expected for a real earthquake. 2D and 3D wave propagation, path effects (such as basin edge amplification and focusing), differences in motions among earthquakes of the same magnitude, and complex site effects are not accounted for with our methodology. For scenarios in which we wish to explore directivity explicitly, ShakeMap includes a tool based on *Rowshandel (2010)* as shown in Figure 3.15 and described in *Directivity*. We are also exploring delivery of scenarios with multiple realizations of spatial variability (see *Future Directions* and *Verros et al. (2016)*.

In terms of generating scenarios with the ShakeMap system, a number of specific considerations and a number of configuration changes are made for scenario events as opposed to actual events triggered by the network. For example, after generating a scenario for a major but hypothetical event, obviously one does not want to automatically deliver the files to customers who are expecting real events. To avoid these sorts of errors, the *Event ID*s for all scenarios are tagged with the suffix *_se*. Such events are recognized by the processing and delivery software, which is configured to handle the scenarios as special cases. Scenarios are also given their own separate space on the webpages. The scenario earthquake ground-motion maps are identical to those made for real earthquakes, with one exception: ShakeMap scenarios are labeled with the word "SCENARIO" prominently displayed to avoid potential confusion with real earthquake occurrences.

See the *Software & Implementation Guide* for additional information on generating earthquake scenarios.

Standardizing Earthquake Scenarios

The USGS has evaluated the probabilistic hazard from active faults in the U.S. for the National Seismic Hazard Mapping Project. From these maps it is possible to prioritize the best scenario earthquakes to be used in planning exercises by considering the most likely candidate earthquake fault first, followed by the next likely, and so on. Such an analysis is easily accomplished by hazard disaggregation, in which the contributions of individual earthquakes to the total seismic hazard, their probability of occurrence, and the severity of the ground-motions are ranked. Using the individual disaggregated components of these hazard maps, a user can select the appropriate scenarios given their location, regional extent, and specific planning requirements.

ShakeMap operators are in the process (early 2016; see *Thompson et al., 2016*) of developing a full suite of scenario ShakeMaps from the disaggregated U.S. National Seismic Hazard Map event catalog produced by *Petersen et al. (2014)*. By disaggregating these hazard maps, we will be able to produce scenarios for a substantial number of the potential significant earthquakes in the United States. It is hoped that these scenarios will satisfy most of the requests that ShakeMap operators typically receive, and the need for ad hoc scenarios will be minimized. Each regional seismic network will be ultimately responsible for producing the scenarios for their region using their local ShakeMap configuration and the fault and magnitude information provided from the hazard maps. For areas outside of the regional networks, we will use the Global ShakeMap system to produce the scenarios. International ShakeMap operators may be able to follow a similar disaggregation of their own seismic hazard maps to generate a suite of scenarios.

After a suite of standardized ShakeMap scenarios is developed for a region or a state, the ShakeMaps can be processed through HAZUS-MH, FEMA's loss and risk estimation software, to develop associated damage estimates and other loss information products. Both Utah and Washington State officials have worked with USGS, FEMA, and other collaborators to produce online collections for scenario exercises and mitigation efforts, shown in Figure 3.16 and Figure 3.17, respectively.

Figure 3.18 provides an example Washington State ShakeMap-based M9.0 Cascadia earthquake scenario. More details can be found online at the Washington State (DNR) Web site.

3.4 Applications of ShakeMap

The distribution of shaking from a significant earthquake, whether expressed as PGA, PGV, or intensity, provides responding organizations a significant increment of information beyond magnitude and epicenter. Real-time ground-shaking maps provide an immediate opportunity to assess the scope and impact of an event. Thus, they can allow emergency managers and responders to determine what areas were likely subjected to the highest intensities and what the probable impacts were in those areas. Importantly, ShakeMap also affords decision-makers a rapid portrayal of those areas that received only weak motions and are likely to be undamaged. The latter areas can potentially be used for mutual aid.

Though initially developed primarily for emergency management, ShakeMaps have been shown to be highly beneficial for other user sectors. These other uses include improved loss estimation, public information and education through the media and webpages, financial decision making, and engineering and seismological research. Some specific examples are provided below for these use cases.

As a side benefit, an intensity-based depiction of shaking hazards through ShakeMap (and DYFI) facilitates the adoption of the intensity scale more generally. Inculcating the populace to earthquake shaking using intensity scales (as opposed to magnitude alone) has become crucial not just for communicating post-earthquake shaking hazards; the color coding and utilization of intensity has more generally helped depict imminent and future shaking hazards. For example, the ShakeMap intensity color palette has been adopted for Earthquake Early Warning (EEW; see for example QuakeAlert) as well as for communicating future hazards through deterministic scenarios and with Probabilistic Seismic Hazard Maps (see *ShakeMap Scenarios*).

3.4.1 Emergency Management and Response

The value of seismic monitoring and ShakeMap was addressed by a report by the National Research Council's (NRC) ad-hoc Committee on the Economic Benefits of Improved Seismic Monitoring (*National Research Council, 20006*). In Chapter 7, "Benefits for Emergency Response and Recovery", the committee refers to the Oct. 16, 1999 M7.1 Hector Mine, California earthquake (ShakeMap shown in Figure 3.20).

Specifically in the context of disaster management and response in the U.S., ShakeMap has been recognized as a top priority:

> *ShakeMap has become a valuable tool to assist emergency responders in identifying the likely extent of earthquake damage. Strong-motion data (now increasingly available in real-time) can be correlated with documentation and evaluation of the performance of the built environment, leading to understanding the causes of earthquake damage and the occurrence of good structural and non-structural performance" ('Western States Seismic Policy Council Policy Recommendation 14-3 <www.wsspc.org/wp-content/.../PR_14-3_SeismicMonitoring_WebPub.pdf>'_).*

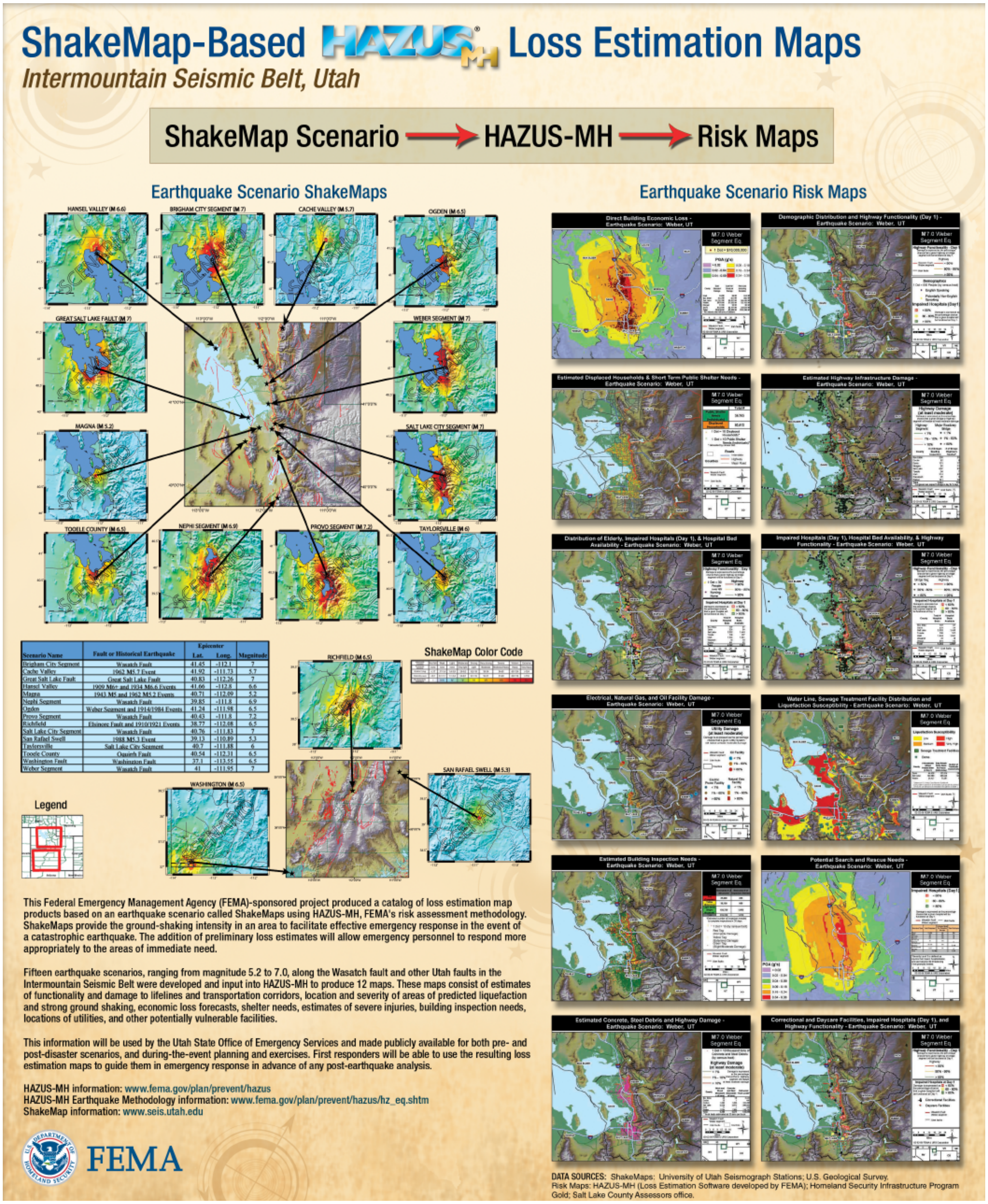


Fig. 3.16: State of Utah using ShakeMap-based earthquake scenario collection. More details can be found online at the FEMA and ShakeOut.org Web sites.

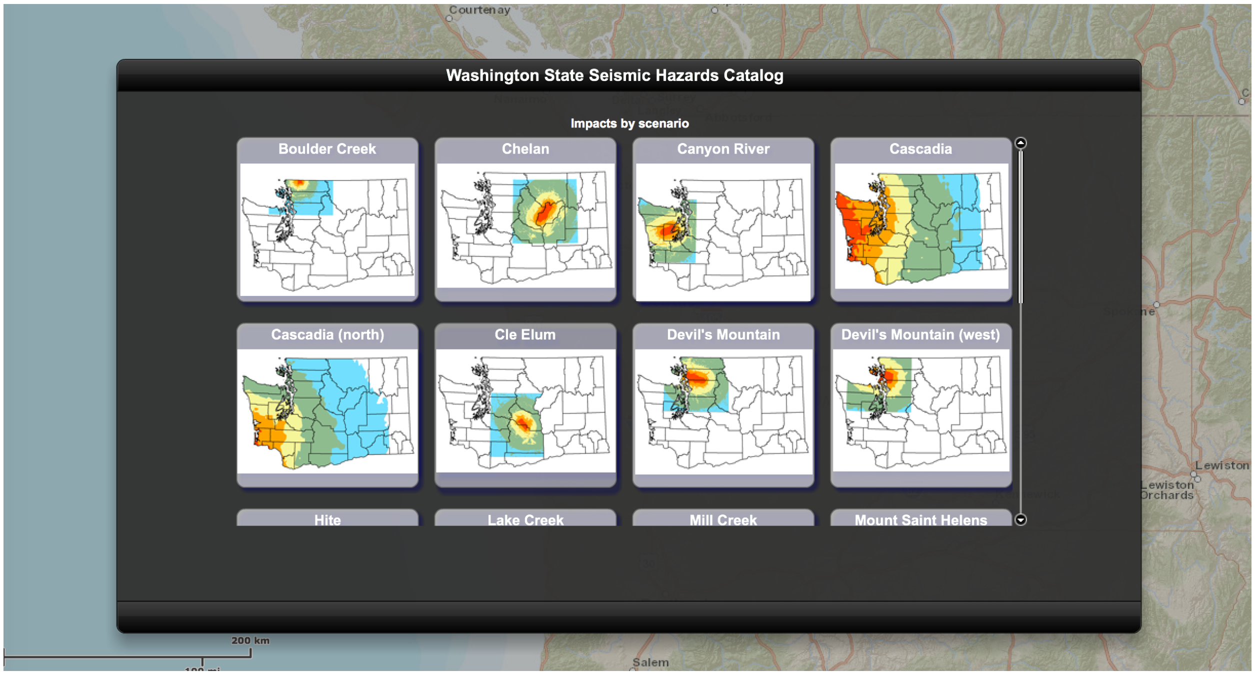


Fig. 3.17: Washington State ShakeMap-based earthquake scenario collection. More details can be found online at the Washington State (DNR) Web site.

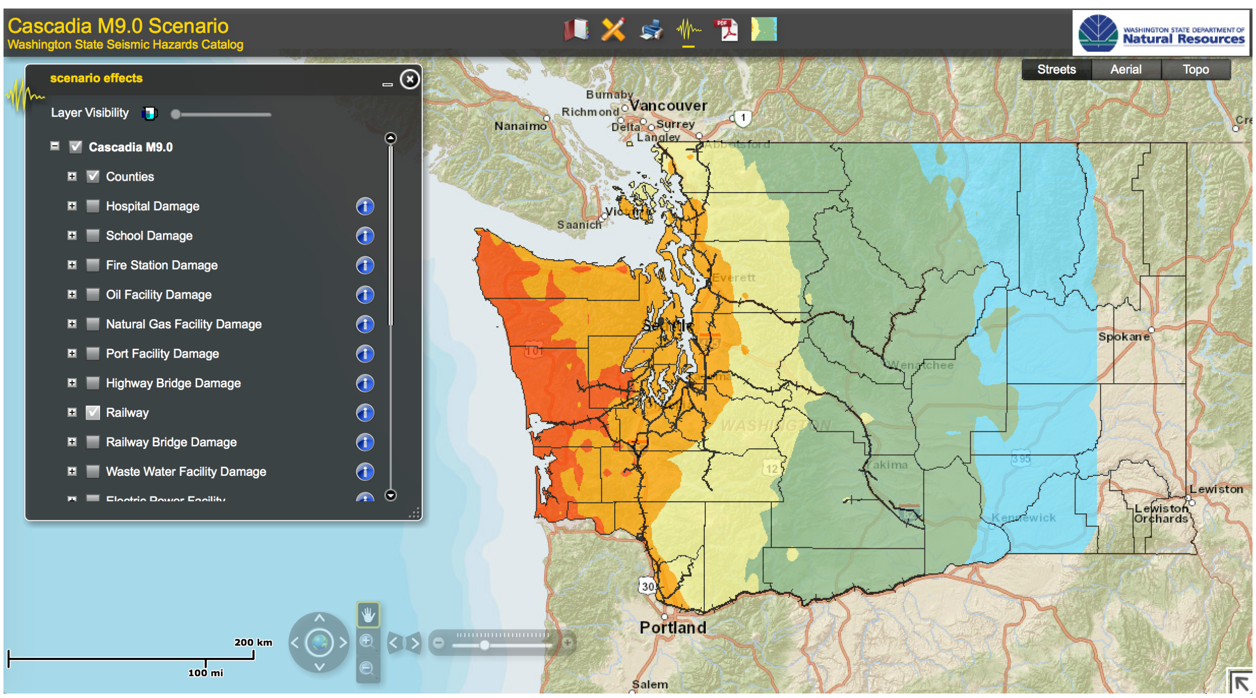


Fig. 3.18: Washington State ShakeMap-based earthquake scenario collection. The selected layer (left) shows railways.

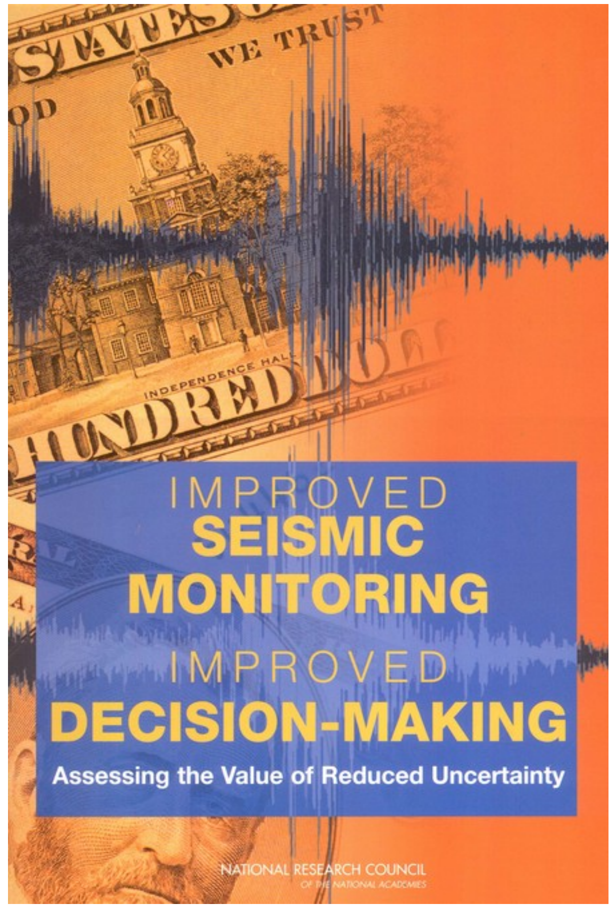
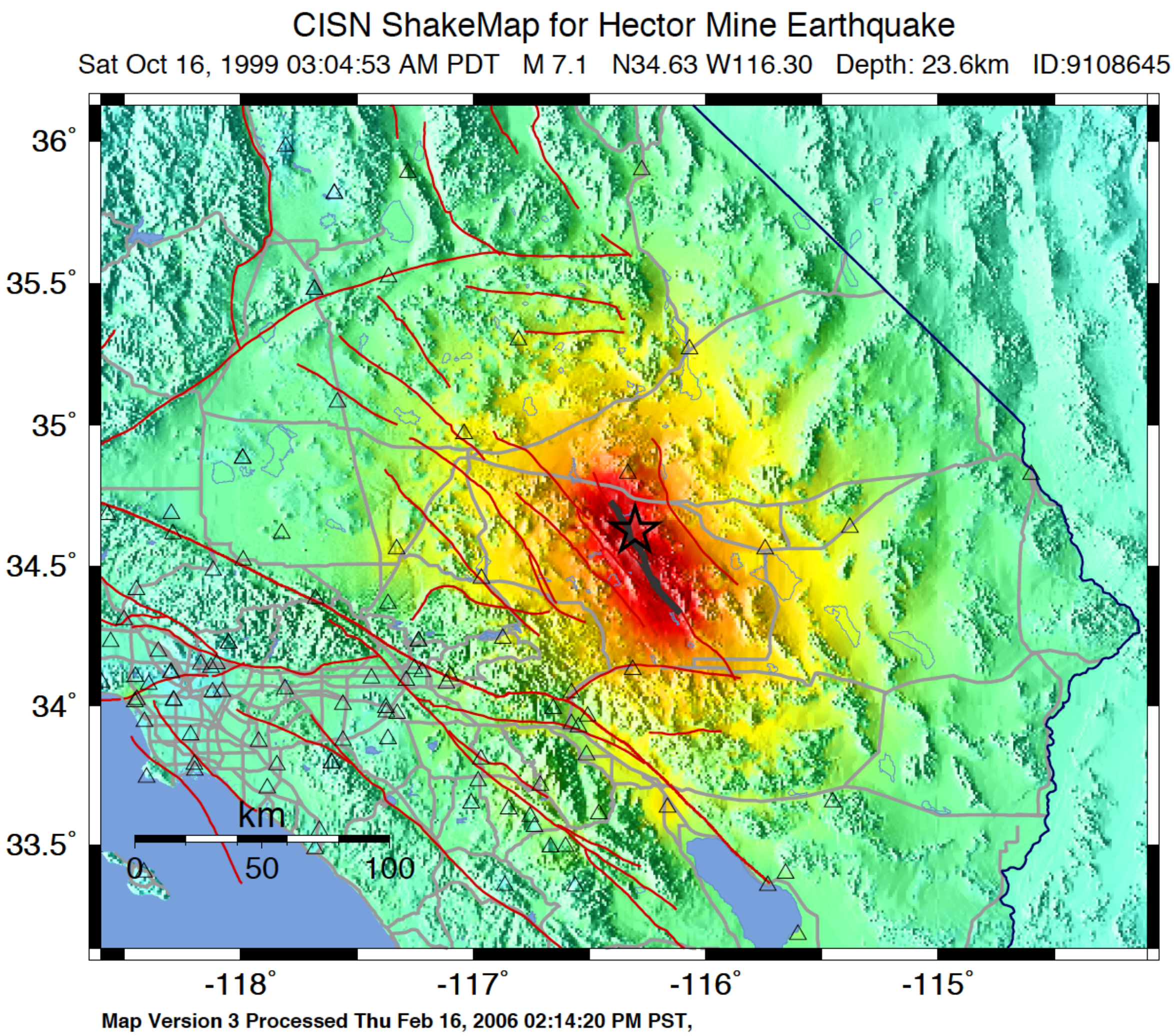


Fig. 3.19: NRC Seismic Monitoring Report

The very rapid availability of earthquake source data—including magnitude, location, depth, and fault geometry—provides basic orienting information for emergency responders, essential information for the news media and the public, and input data for other applications and response-relevant products. Maps of ground shaking intensity (ShakeMap) have many important applications in emergency management. Because ShakeMap is available via the Internet, all emergency responders at all levels of government and the private sector have access to the same rapidly available information. With this information, responders can quickly assess the scope of the emergency and mobilize resources accordingly. Early reconnaissance efforts can target areas known to have been shaken most severely, and key emergency services including search and rescue, emergency medical response, safety assessment of critical facilities, and shelter and mass care can be expedited based on a more rapid identification of incident location. Monitored information is also useful for rapidly assessing situations in which a large, widely felt earthquake occurs but causes little damage (such as the Hector Mine earthquake of October 16, 1999). Clearly, there are significant economic benefits in scaling a response to the consequences of an event, including no response for an earthquake that requires none.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 3.20: Instrumental Intensity ShakeMap for the 1999 M7.1 Hector Mine, CA earthquake. (Map regenerated in 2006)

Similarly, a report by the National Science and Technology Council Subcommittee on Disaster Reduction* (Grand Challenges for Disaster Reduction: Priority Interagency Earthquake Implementation Actions) describes "Grand Challenge 1":

> *Provide hazard and disaster information where and when it is needed. [...] Expand the Advanced National Seismic System to improve seismic monitoring and deliver rapid, robust earthquake information products; For all urban areas with moderate to high seismic risk, produce ShakeMaps that show the variation of shaking intensity within minutes after an earthquake based on near real time data transmission from densely spaced seismic networks.*

One of the earliest examples of the use of ShakeMap for emergency management and response was the the M7.1 Hector Mine earthquake of October 16, 1999 (see Figure 3.20). This event provides an important lesson in the use of ShakeMap to assess the scope of an event and to determine the level of mobilization necessary. The Hector Mine earthquake produced ground motion that was widely felt in the Los Angeles basin and, at least in the immediate aftermath, required an assessment of potential impacts. It was rapidly apparent, based on ShakeMap, that the Hector Mine earthquake was not a disaster, and despite an extensive area of strong ground shaking, only a few small desert settlements were affected. Thus, mobilization of a response effort was limited to a small number of companies with infrastructure in the region and brief activations of emergency operations centers in San Bernardino and Riverside Counties and the California Office of Emergency Services (now the California Emergency Management Agency, or CalEMA).

While prioritizing earthquake response and management is considered the primary goal of systems like ShakeMap, unnecessary response to an earthquake—although not as costly as inadequate or misguided response in a real disaster—can be avoided with proper well-constrained shaking information. Had the magnitude-7 earthquake occurred in urban Los Angeles or another urban area in California, ShakeMap could be employed to quickly identify the communities and jurisdictions requiring immediate response. To help facilitate the use of ShakeMap in emergency response, ShakeMap is now provided to organizations with critical emergency response functions automatically through USGS webpages, ShakeCast, and similar tools.

3.4.2 Loss Estimation

The Federal Emergency Management Agency (FEMA) employs ShakeMap for post-earthquake damage assessments. USGS generates customized, formatted ESRI shapefiles for direct input into FEMA's Hazards U.S. (HAZUS-MH ; *FEMA (2006)* loss estimation software. The customization includes specific contour intervals for all events, geometric-mean ground motions (as opposed to ShakeMap standard maximum component), and peak ground velocity in units of inches/sec rather than cm/s. The HAZUS-formatted ShakeMap shapefiles are made available to FEMA for scenarios and all significant domestic (U.S.) earthquakes via webpages and ArcGIS services (see *Web Mapping (GIS) Services*).

The use of ShakeMaps as the shaking hazard input into HAZUS is a major improvement in loss-estimation accuracy because actual ground-motion observations are used directly to assess damage, rather than relying on simpler estimates based on epicenter and magnitude alone, or from predefined earthquake scenarios built into the HAZUS software.

FEMA's HAZUS loss estimates can be important for coordinating state and federal response efforts, including Disaster Declarations. HAZUS's detailed impact reports can provide focus to the mobilization of resources and expedite the local, state, and federal disaster declaration process, thus initiating the government's response and recovery machinery. ShakeMap, when overlaid with inventories of critical lifelines and facilities (e.g., hospitals, utilities, and substations), highways and bridges, and vulnerable structures, provides an important means of prioritizing response. Such response activities can include shelter and mass care, mutual aid assignments, emergency management, damage and safety assessment, utility and lifeline restoration, and emergency public information.

As of 2015, the HAZUS-MH software is run interactively, not automatically, so qualified FEMA personnel must be on hand to initiate HAZUS calculations and post the results. In addition, for heavily populated areas (such as major cities in California), HAZUS software can take a few hours to compute losses. Thus, initial HAZUS-based losses are well behind initial ShakeMap and PAGER results, and of course they are limited to earthquakes in the U.S. However, the HAZUS results provide much greater detail and information about infrastructure than PAGER-based aggregated losses.

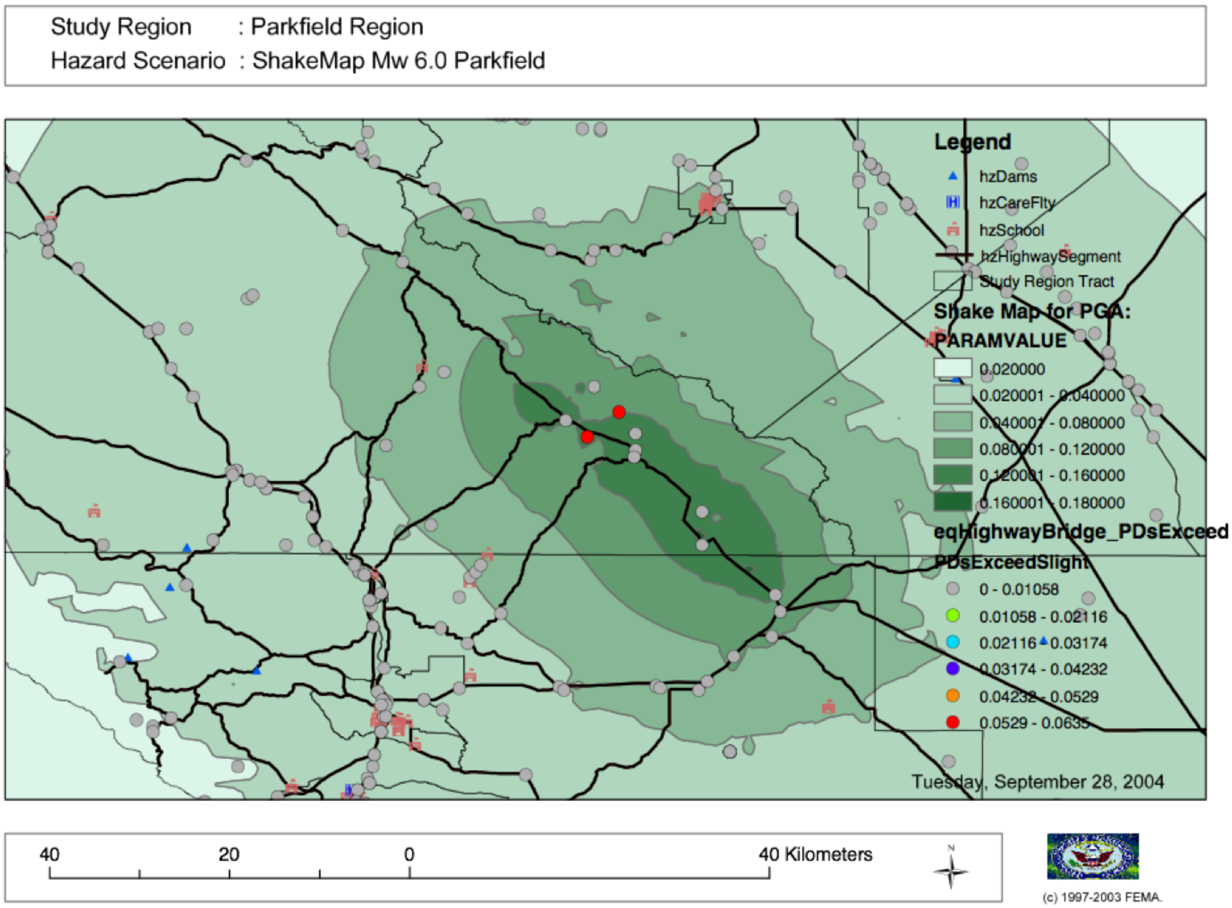


Fig. 3.21: 2004 M6.0 Parkfield, CA earthquake ShakeMap shapefiles (green polygons) and HAZUS estimated impact to selected infrastructure (circles) examined. Figure courtesy of D. Bausch, FEMA.

As described in the section on Scenarios (*ShakeMap Archives*), HAZUS-MH is the standard approach for delivering loss estimates for ShakeMap scenarios domestically. For real events, the ShakeMap-to-HAZUS handoff has been formalized with a liaison agreement (a Memo of Understanding, MOU) involving Doug Bausch, formerly of FEMA Region VIII, and David Wald at the USGS NEIC. Because ShakeMap shaking estimates evolve with time, and HAZUS loss estimates take time to compute, it is essential that direct communications between the two agencies takes place immediately after a serious earthquake to optimize loss estimates.

The USGS-FEMA partnership has been activated for several domestic earthquakes since this system was put into place, including 2004 M6.0 Parkfield, California; 2006 M6.0 Kiholo Bay, Hawaii; 2010 M7.2 Baja California, Mexico; 2011 M5.6 Prague, Oklahoma; 2011 M5.8 Mineral, Virginia; the M6.0 2015 American Canyon, California; and several other events. The same approach has been tested and applied retrospectively against the 1994 M6.7 Northridge, California and 1989 M6.9 Loma Prieta, California earthquakes, among others.

3.4.3 Financial Sector Decision-Making

Post-earthquake financial decision making has evolved considerably over the past decade. Insurers and reinsurers, private companies, governments, and aid organizations have shown increasing creativity in the utilization of near–real-time earthquake information for their own loss estimation, financial adjudication, and situational awareness. Such financial analyses can be of significant benefit to stakeholders, facilitating risk-transfer operations, fostering sensible management of risk portfolios, and assisting disaster responders. Ultimately, these improvements translate to benefits for the public and those at risk (*Franco, 2015*).

In general, there are three categories of post-earthquake financial services and decision making: 1) analysis of expected losses arising from an actual event against a portfolio of exposures; 2) the triggering of payments for parametric insurance products; and 3) the use of quantitative loss estimates to manage disaster response and aid. Business and public-sector portfolio managers can employ tools like ShakeCast or in-house applications to automatically retrieve and compute losses based on pre-assigned fragility curves. Within the (re)insurance sector, catastrophe (CAT) bonds and contingency loans based on earthquake risk models are often triggered via parametric analyses, which are dependent on earthquake parameters or intensity-measure (IM) estimates as well as their uncertainties.

Anticipating potential losses and acting rapidly and accordingly is also of utmost importance to emergency management and disaster aid communities. Estimated losses constitute vital input for rapid situational awareness, facilitating decision-making on whether or not to commit and deploy resources, and to what level.

USE CASE #1

The Inter-American Development Bank http://www.iadb.org (IADB) employs ShakeMap for objective post-earthquake assessments for within 72 hours of any significant earthquake in Latin America and the Caribbean (LACR). IADB's Contingent Credit Facility Loans has set up disaster contingency loans for up to several hundred million USD, conditional on predefined levels of population exposed to ShakeMap intensity VI and higher. Typically, loans can be distributed when the population experiencing intensity VI or higher reaches at least 2% of the population within the coverage area. Loans are available in six LACR countries during the period of availability (J. Martinez, IADB, written comm., 2014).

To a large extent, the advancement of post-earthquake financial instruments has been facilitated by the availability of rapid and accurate earthquake parameters and more quantitative geospatial hazard information. Commensurately, USGS products like ShakeMap and PAGER have evolved to further accommodate specific requirements of the financial sector. For instance, improved approaches for quantifying uncertainty can better inform loss estimates, and historical ShakeMap Atlas data can assist in loss-model calibration. In addition, USGS now provides PAGER loss estimates broken down by country to fulfill the need required in the CAT bond and contingency loan arena, while still remaining within the confines of reasonable spatial accuracy. Similarly, requests have been made by U.S. State governments to further compute losses at the state level, although such resolution is not yet warranted, particularly in areas of sparse real-time strong-motion instrumentation. Lastly, for many uses, the automatic retrieval and processing of ShakeMaps has been facilitated via GeoJSON feeds, webmapping servers, and the ShakeCast systems.

Several types of data and information products available or under development that may be of benefit to the financial sector. The generation of suites of standardized earthquake scenarios—both domestic and internationally—is underway, and an update of the global Atlas of ShakeMaps has been completed (see *ShakeMap Archives*).

There are several continuing challenges under consideration and scrutiny: implementing directivity; computing and depicting spatial ground motion correlations; improving approaches for quantifying and conveying uncertainties; and creating more explicit ShakeMap policy and version-control documentation. *Wald and Franco (2016)* describe how these advances may in turn facilitate the appearance of new and more refined financial instruments and insurance products.

3.4.4 Public Information and Education

The rapid availability of ShakeMap on the Internet, combined with the urgent desire for information following a significant earthquake, makes this mapping tool a huge potential source of public information and education. In instances in which an earthquake receives significant news coverage, the ShakeMap site and "Did You Feel It?" (DYFI) receive an enormous influx of visitors (*Wald et al., 2011*). Such opportunities are amplified by widespread adoption of ShakeMap into media and educational materials by other institutions.

ShakeMap's intensity scale is key for introducing and impressing upon the public and the media the importance of macroseismic intensity, rather than the continuing sole dependence on magnitude as the scale of reference for earthquakes. Although Japanese Meterological Agency (JMA) Intensity (.e.g., *JMA, 1996*) differs slightly from its U.S. counterpart, Modified Mercalli Intensity (MMI)—JMA's is strictly instrumentally-derived—it is widely used and understood in Japan (e.g., *Celsi et al., 2005*). JMA has successfully made intensity the norm for communicating to the Japanese population about real-time and future earthquake hazards via television, smartphone, web content, annual earthquake drills, and the educational system. Because JMA intensity is widely understood, the public is be more attuned to earthquake risks than populations familiar only with magnitude descriptions of earthquakes (e.g., *Celsi et al., 2005*).

> *Earthquake education also occurs through the media. The anchoring effect we report may be lessened significantly if the press consistently used the Mercalli scale and helped to educate the public about the scale. Research should be conducted to better understand if and how news organizations can successfully utilize the Mercalli scale in communicating earthquake information. Alternative formats, for example, using letters rather than Roman numerals for the categories, may ameliorate the confusion between magnitude and Mercalli scales. The experience in Japan provides support for the idea that laypeople can learn to use the two scales side by side. The Japanese media report both intensities and magnitude, with viewers maintaining a clearer understanding of the relationship between magnitude and intensity. In Japan, the overall magnitude and the intensity are both instrument numbers, with the latter being location-specific.*

The acclimatization of the public to intensity is inline with the findings of *Gomberg and Jokobitz (2013)*:

> *Simpler messaging and explanations are needed by some users, and this may be achieved by developing two styles of some products, one designed for nontechnical users and the other tailored for engineers and scientists. The tangible impacts of an earthquake must be conveyed more simply and succinctly, employing a scale useful for decision-making at the regional and local levels.*

Acknowledging the importance of ShakeMap as a tool for public information and education, considerable effort was taken to provide a range of formats suitable for broadcast and webpages. Initially "Media Maps", simplified versions of the Instrumental Intensity maps, were packaged in a way that makes them more suitable for broadcast to low-resolution devices, such as TV monitors—roads and borders are thicker, fonts are larger, and the title and intensity scale are simplified—and a "TV guide" information sheet was provided to supplement the Media Maps, to allow easier delivery of basic earthquake information. These formats have naturally evolved to GIS, KML, and now interactive (zoomable) maps that allow customization of the basemap layers and other content. Such interactive maps are in favor in newsrooms and educational contexts.

However, some of the static maps have made for the most widespread distribution. A widely used graphic (Figure 3.22), for example, compares ShakeMap-generated intensities for the 1994 Northridge earthquake, a shallow crustal earthquake near Los Angeles, with the 2001 deep, intraslab Nisqually, WA earthquake. This figure was reprinted in numerous reports, textbooks, classes, reports, and briefings, including Putting Down Roots and the *National Research Council*.

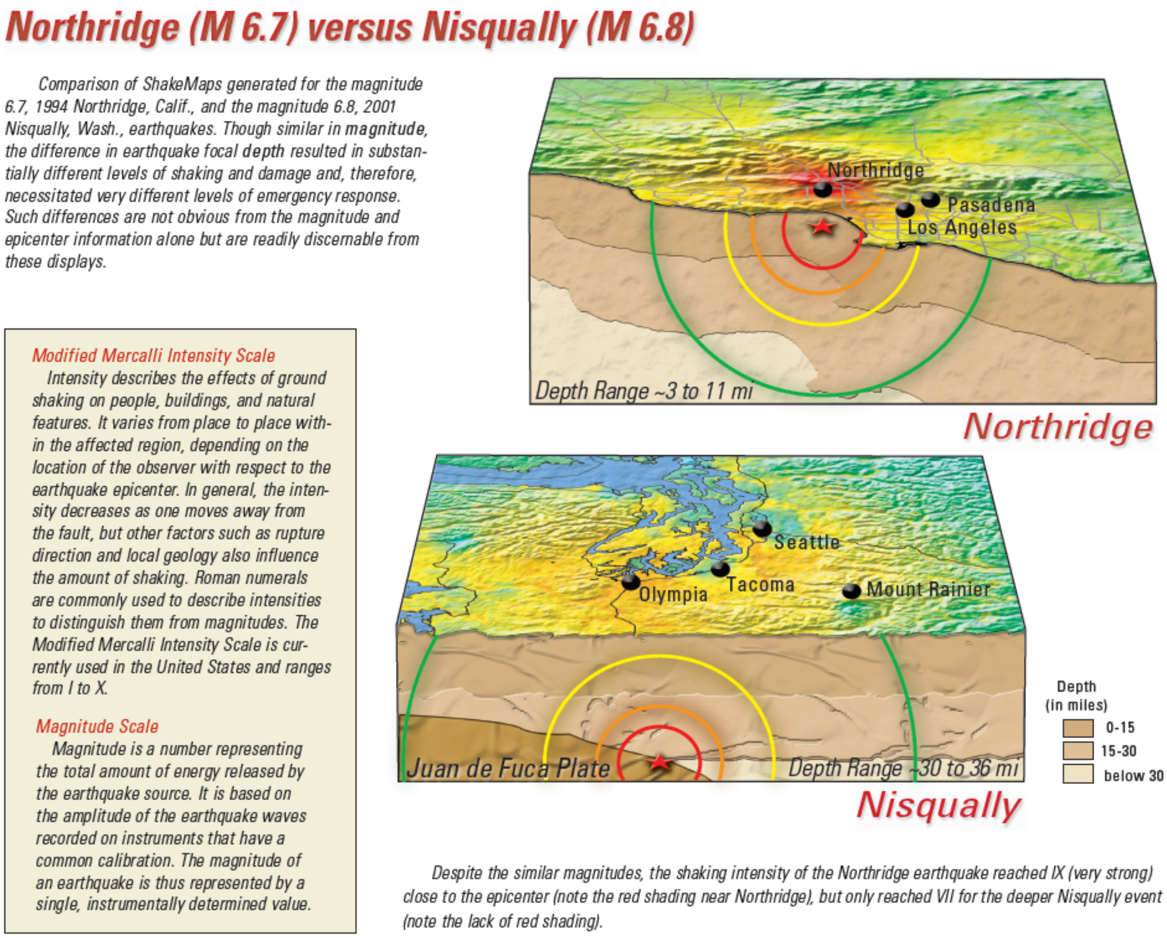


Fig. 3.22: Widely adopted graphic of comparing ShakeMaps for the 2001 M6.8 Nisqually, WA and 1994 M6.7 Northridge, CA earthquakes, showing how distance from an earthquake affects the level of shaking experienced. Even though the magnitude of the Nisqually earthquake was slightly greater than that of the Northridge earthquake, the shaking was lower on average, primarily because the fault that ruptured during the Northridge earthquake was shallower (5-20km deep) than that of the Nisqually earthquake (about 45-50km deep).

The continued longterm education of the public to intensity continues through many TV channels and other means, for instance, in academic courses (e.g., Larry Braile's undergraduate courses), textbooks (e.g., *Yeats, 2004* "Living with Earthquakes in the Pacific Northwest"), and even Wikipedia.

3.4.5 Emergency Preparedness

One of the leading tools for earthquake emergency preparedness has been the widespread adoption of "ShakeOut" and other earthquake drills and planning scenarios. In many of these cases, ShakeMap is employed both for developing the framework for portraying each earthquake in its hazard context and for computing loss estimates to examine and communicate its potential societal impact. The initial success of the Great Southern California ShakeOut (*Jones et al. (2011)*) has been built by SCEC, USGS, and others into a worldwide annual exercise (on Oct 15th of each year) involving millions of participants.

On a statewide basis, exercises take place in several of the more tectonically active areas of the country, such as ShakeOuts in Utah and the 2012 Evergreen Earthquake Exercise ShakeMaps in Washington State.

Nationwide, FEMA's National Level Exercises (NLEs) program is another source for planning for complex, whole-community, large-scale disasters and emergencies. Here, too, NLEs often employ ShakeMap as the basis for their exercises. The ShakeMap-HAZUS combination was to support the New Madrid 2011 NLE, involving an M7.7 New Madrid region mainshock and several significant aftershocks. In 2014, the "Capstone Exercise" NLE was a complex emergency preparedness exercise including the Alaska Shield 2014 exercise, sponsored by the State of Alaska to commemorate the 50th anniversary of the 1964 Great Alaskan Earthquake. The exercise also involved significant damage from earthquake shaking as well as tsunami, triggering impacts in the Pacific Northwest. The Department of Defense (DOD) aligned key components of the Capstone exercise with a connected "Ardent Sentry" table-top exercise with the same ShakeMap input in order for DOD to focus on defense support to civilian authorities.

Internationally, USGS participates (through the National Oceanic and Atmospheric Association, NOAA) in an annual "Caribe Wave" earthquake and tsunami exercise for the Caribbean region (*IOC, 2012*; see Figure 3.23). The USGS ShakeMap and PAGER group also work directly with the U.S. Agency for International Development (USAID) Office of Foreign Disaster Assistance (OFDA), the World Bank, and Geohazards International (GHI) (among many other agencies, countries, and NGOs) to develop global planning exercises and scenarios.

3.4.6 Earthquake Engineering and Seismological Research

For potentially damaging earthquakes, ShakeMap produces response spectral acceleration grid values for three periods (0.3, 1.0, and 3.0 sec). The spectral acceleration values are used for loss estimation, as mentioned above, yet these measures also serve many earthquake engineering analysis purposes. In a post-earthquake environment, information from engineering analyses of structures (including via ShakeCast, see below) provides a framework for post-earthquake occupancy, tagging, and damage inspection by civil engineers.

ShakeMap products and metadata aggregate earthquake source information, shaking intensity measures (IMs) including both seismic and macroseismic observations, and fault geometries and station-sources distances. In addition to providing these data systematically for recent events, the same constraints are made available for numerous earthquakes, for recent events as well as historical events (*ShakeMap Archives*).

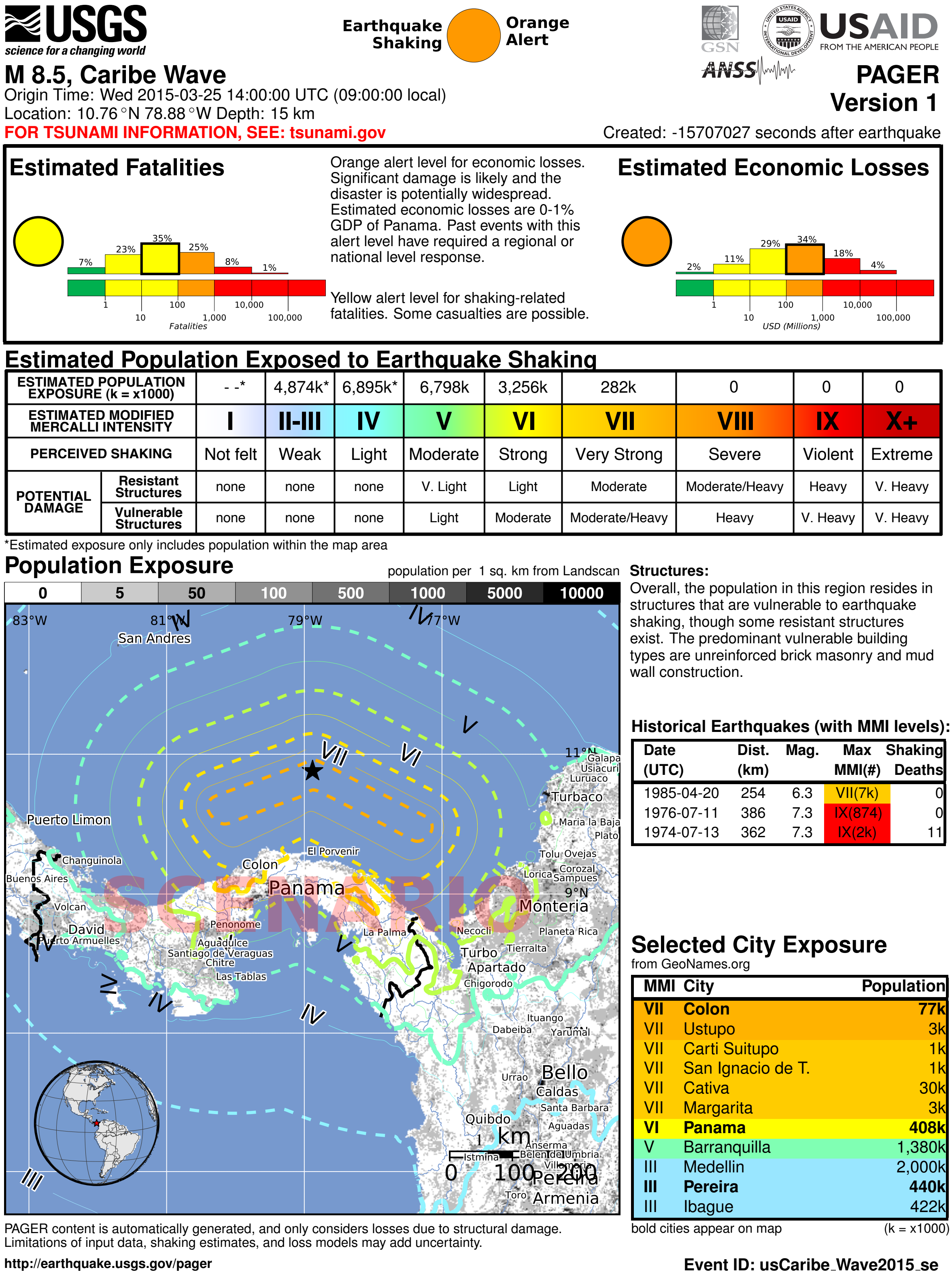
The aggregation of earthquake information and fault geometries—in conjunction with reported shaking and macroseismic data—provide the basis for analyses of best-estimate ground motion IMs at specific sites for comparison with human behavior and response by the natural and built environments. Here is a sampling of the range of studies these products motivate and facilitate:

Example Engineering Research and Analyses:

- Analyses of potential damage to column/beam welds in steel buildings following the 1994 Northridge earthquake. *ATC 2002*.
- ATC-54: Guidelines for using strong-motion data and ShakeMaps in Post-Earthquake Response. *ATC 2002*.
- An Empirical Model for Global Earthquake Fatality Estimation. *Jaiswal and Wald (2010)*.
- Guidelines for the Collection of Consequence Data, Global Earthquake Consequences Database Global Component Project. *Pomonis and So (2011)*.
- ShakeCast Case Study on Nevada Bridges. *Biasi et al (2016)*.

Example Seismological Research and Analyses:

- Intensity attenuation for active crustal regions. *Allen et al, 2012*.
- Ground Motion to Intensity Conversion Equations (GMICEs): A Global Relationship and Evaluation of Regional Dependency. *Caprio et al. (2015)*.
- Fault extent estimation for near-real time ground shaking map computation purposes. *Convertito et al. (2011)*.



USGS
science for a changing world

Earthquake Shaking — Orange Alert

GSN ANSS USAID FROM THE AMERICAN PEOPLE

PAGER
Version 1

M 8.5, Caribe Wave
Origin Time: Wed 2015-03-25 14:00:00 UTC (09:00:00 local)
Location: 10.76 °N 78.88 °W Depth: 15 km
FOR TSUNAMI INFORMATION, SEE: tsunami.gov

Created: -15707027 seconds after earthquake

Estimated Fatalities

Orange alert level for economic losses. Significant damage is likely and the disaster is potentially widespread. Estimated economic losses are 0-1% GDP of Panama. Past events with this alert level have required a regional or national level response.

Yellow alert level for shaking-related fatalities. Some casualties are possible.

Estimated Economic Losses

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	4,874k*	6,895k*	6,798k	3,256k	282k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area

Population Exposure

population per 1 sq. km from Landscan

0	5	50	100	500	1000	5000	10000

Structures:
Overall, the population in this region resides in structures that are vulnerable to earthquake shaking, though some resistant structures exist. The predominant vulnerable building types are unreinforced brick masonry and mud wall construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1985-04-20	254	6.3	VII(7k)	0
1976-07-11	386	7.3	IX(874)	0
1974-07-13	362	7.3	IX(2k)	11

Selected City Exposure
from GeoNames.org

MMI	City	Population
VII	**Colon**	**77k**
VII	Ustupo	3k
VII	Carti Suitupo	1k
VII	San Ignacio de T.	1k
VII	Cativa	30k
VII	Margarita	3k
VI	**Panama**	**408k**
V	Barranquilla	1,380k
III	Medellin	2,000k
III	**Pereira**	**440k**
III	Ibague	422k

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage.
Limitations of input data, shaking estimates, and loss models may add uncertainty.

http://earthquake.usgs.gov/pager

Event ID: usCaribe_Wave2015_se

Fig. 3.23: Annual "Caribe Wave" earthquake and tsunami exercise for the Caribbean region.

- Bayesian Estimations of Peak Ground Acceleration and 5% Damped Spectral Acceleration from Modified Mercalli Intensity Data*. *Ebel and Wald (2003)*.
- Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap. *Faenza and Michilini (2010)*
- A Global Earthquake Discrimination Scheme to Optimize Ground-Motion Prediction Equation Selection. *Garcia et al. (2012b)*.

3.5 Related Systems

Here is a brief listing of USGS Earthquake Hazards Program rapid earthquake information products:

- Earthquake Notification System sends automated, customizable notifications of earthquakes through email, pager, or cell phone.
- Realtime Earthquake Map: Automatic maps and event information displayed online within minutes after earthquakes worldwidema
- ShakeMap automatically generates maps displaying instrumentally measured shaking intensities.
- Did You Feel It?: Map of earthquake effects derived from citizen input via online Web forms
- *PAGER* (Prompt Assessment of Global Earthquakes for Response) rapidly compares the population exposed to various shaking intensities to estimate likely fatalities and economic losses
- CISN Display: Stand-alone application that graphically alerts users, in near real time, of earthquakes and related hazards information.
- ShakeCast: An application for automated delivery of ShakeMaps and potential damage or inspection priority for specific user-selected facilities.
- ShakeAlert: Prototype Earthquake Early Warning (EEW) System.

While ShakeMap has met with success as a standalone product for communicating earthquake effects to the public and the emergency response and recovery community, it is increasingly being incorporated into value-added products that help in the assessment of earthquake impacts for response management and government officials.

As discussed in detail the *Technical Guide*, ShakeMap is augmented by DYFI input for constraining intensities, and from those, estimates of peak ground motions (in some cases, and for some regions), as shown in Figure 3.24. DYFI and ShakeMap in conjunction then represent the shaking hazard input for two other primary systems that estimated losses: ShakeCast and PAGER. ShakeCast is intended for specific users to prioritize response for specific user-centric portfolios of facilities; PAGER is for more general societal-impact assessments, providing estimated loss of life and economic impacts for the region affected.

3.5.1 ShakeCast

ShakeCast is a freely available post-earthquake situational awareness application that automatically retrieves earthquake shaking data from ShakeMap, compares intensity measures against users' facilities, and generates potential damage assessment notifications, facility damage maps, and other web-based products for emergency managers and responders.

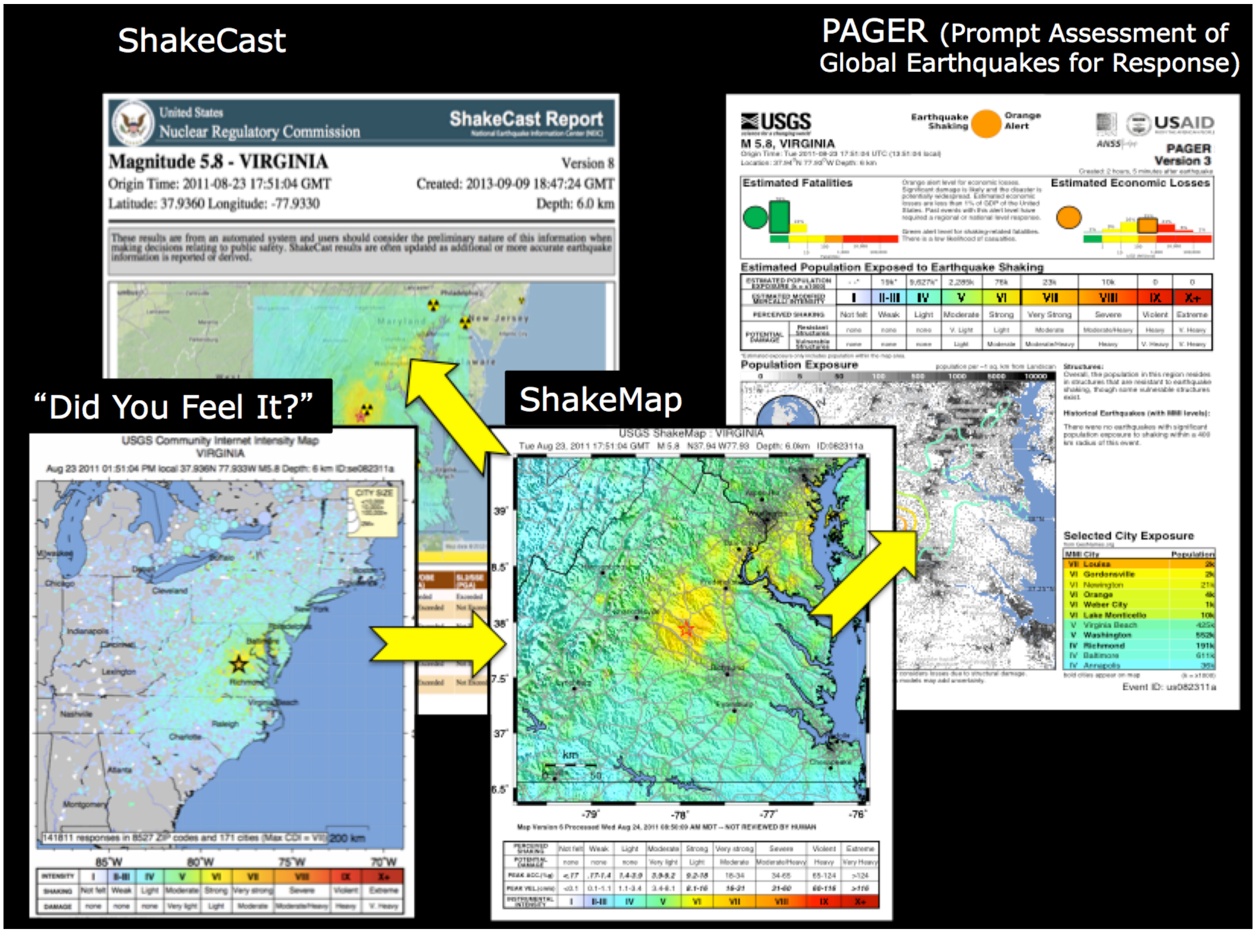


Fig. 3.24: Interplay between ShakeMap, DYFI, ShakeCast, and PAGER.

USE CASE #2

The California Department of Transportation (Caltrans) employs ShakeMap for post-earthquake overpass and bridge assessments for significant California earthquakes:
The Caltrans ShakeCast system performed reliably and as expected during the Napa earthquake. The system delivered key information on the potential impacts to the state bridge inventory within 11 minutes of the event. Of a total of 2720 state bridges within the ShakeMap region, 87 state bridges were identified by ShakeCast as having undergone significant ground shaking and were assigned an inspection priority state. Of the 87 state bridges identified, 9 were later confirmed to have sustained minor damage. These 9 state bridges were ranked in the top 40% of the ShakeCast list. –(*Turner, 2014*)

ShakeCast, short for ShakeMap Broadcast, is a fully automated system for delivering specific ShakeMap products to critical users and for triggering established post-earthquake response protocols. ShakeMap was developed and is used primarily for emergency response, loss estimation, and public information; for an informed response to a serious earthquake, critical users must go beyond just looking at ShakeMap, and understand the likely extent and severity of impact on the facilities for which they are responsible. To this end, the USGS has developed ShakeCast.

ShakeCast allows utilities, transportation agencies, businesses, and other large organizations to control and optimize the earthquake information they receive. With ShakeCast, they can automatically determine the shaking value at their facilities, set thresholds for notification of damage states for each facility, and then automatically notify (by pager, cell phone, or email) specified operators and inspectors within their organizations who are responsible for those particular facilities so they can set priorities for response.

USE CASE #3

"Thought you might like to see the [Division of Safety of Dams] ShakeCast message for the recent Napa [Aug, 2014] Earthquake. We have since divided the 1250 dams into three fragility classes (called levels of concern). The message provides explicit instructions on what action to take for each dam and transmits owner contact information. The message was received in my inbox 16 minutes after the earthquake, which was about 10 minutes after the ShakeMap version 1 was released. The technology has become very well accepted by the field inspectors. Thanks for such a great product." –W. A. Fraser, C.E.G., Chief, Geology Branch, CA Division of Safety of Dams, Sacramento, CA.

3.5.2 PAGER

Another important USGS product that uses ShakeMap output as its primary data source is *PAGER* (Prompt Assessment of Global Earthquakes for Response), an automated system that produces content concerning the impact of significant earthquakes around the world, informing emergency responders, government and aid agencies, and the media of the potential scope of the disaster. PAGER rapidly assesses earthquake impacts by comparing the population exposed to each level of shaking intensity with models of economic and fatality losses based on past earthquakes in each country or region of the world. Earthquake alerts—which were formerly sent based only on event magnitude and location, or population exposure to shaking—will now be generated based also on the estimated range of fatalities and economic losses.

PAGER alerts are based on the "Earthquake Impact Scale" developed by *Wald et al. (2011)*.

3.5.3 Public and Private Sector Tools

Alternatives, modifications, and enhancements to the ShakeMap methodology are used widely around the world. Likewise, downstream derivative products and systems for loss estimation are widely employed, both in the public and private sector. What follows is a brief (and incomplete) description of some of these systems. Many proprietary hazard and loss modeling systems exist in the private sector, and typically they are openly described or referenced.

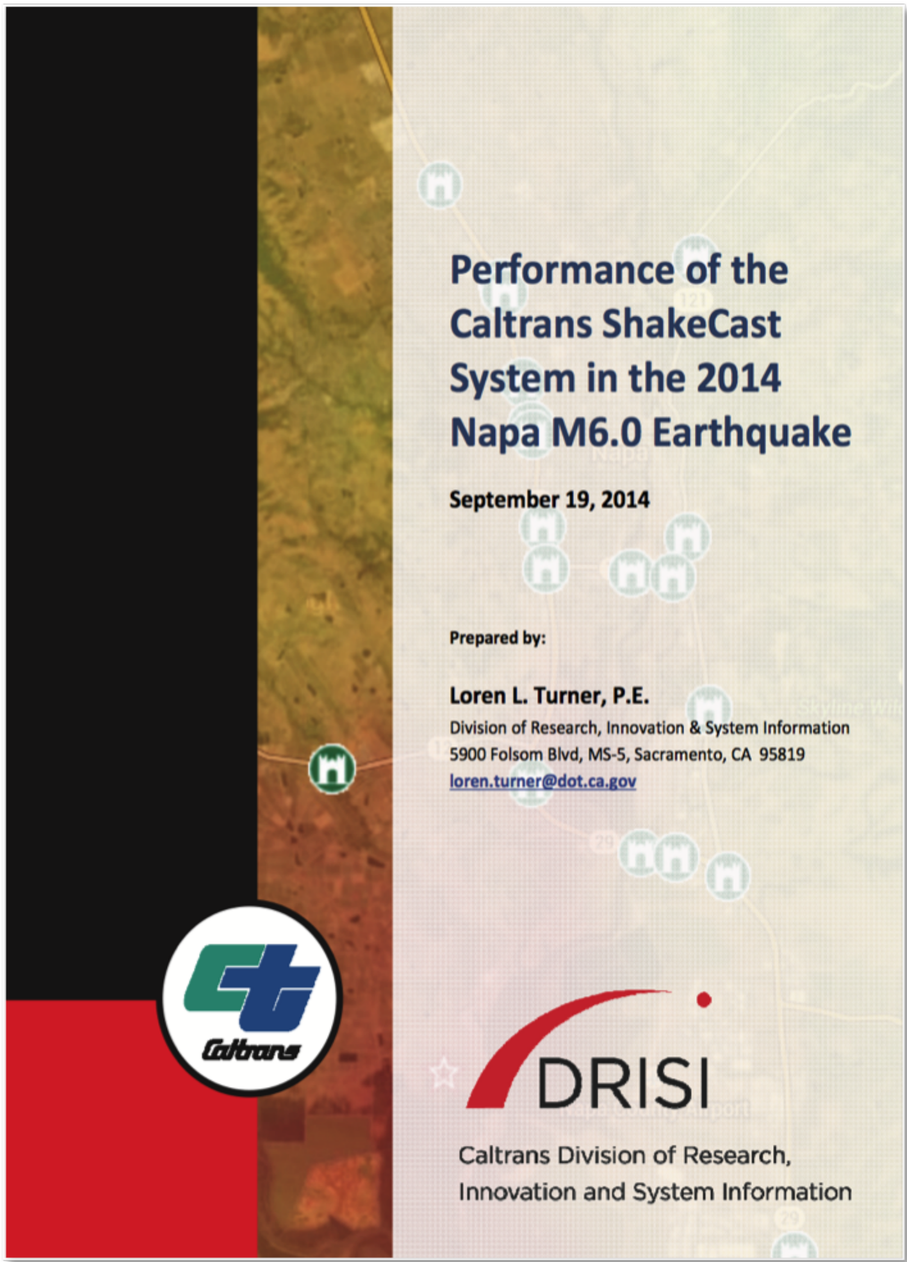
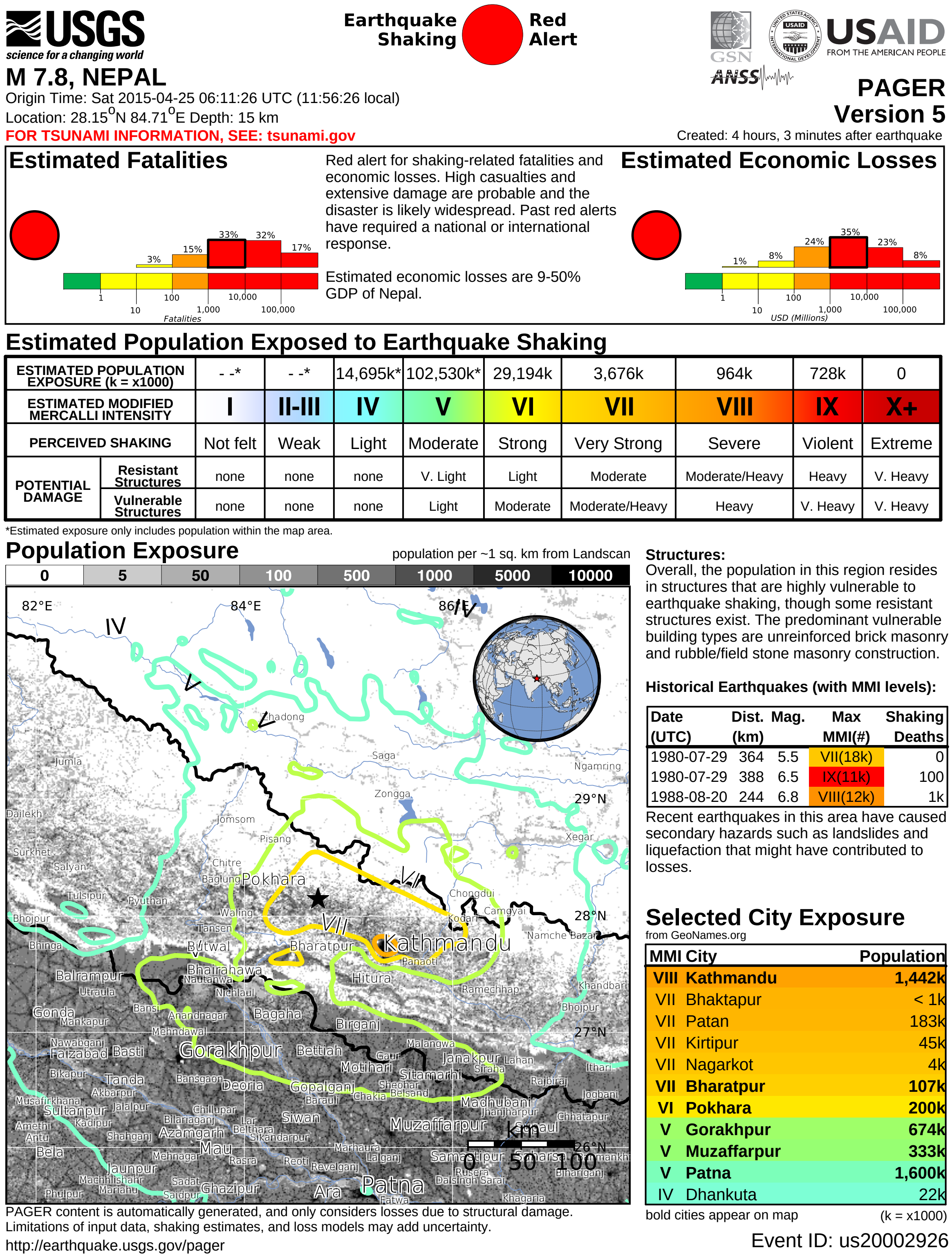


Fig. 3.25: Caltrans ShakeCast report for the 2011 M6.0 Napa, CA earthquake.



science for a changing world

Earthquake Shaking Red Alert

GSN ANSS

USAID FROM THE AMERICAN PEOPLE

M 7.8, NEPAL

Origin Time: Sat 2015-04-25 06:11:26 UTC (11:56:26 local)
Location: 28.15°N 84.71°E Depth: 15 km
FOR TSUNAMI INFORMATION, SEE: tsunami.gov

PAGER Version 5

Created: 4 hours, 3 minutes after earthquake

Estimated Fatalities

3% 15% 33% 32% 17%
1 10 100 1,000 10,000 100,000
Fatalities

Red alert for shaking-related fatalities and economic losses. High casualties and extensive damage are probable and the disaster is likely widespread. Past red alerts have required a national or international response.

Estimated economic losses are 9-50% GDP of Nepal.

Estimated Economic Losses

1% 8% 24% 35% 23% 8%
1 10 100 1,000 10,000 100,000
USD (Millions)

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	14,695k*	102,530k*	29,194k	3,676k	964k	728k	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0 5 50 100 500 1000 5000 10000

Structures:

Overall, the population in this region resides in structures that are highly vulnerable to earthquake shaking, though some resistant structures exist. The predominant vulnerable building types are unreinforced brick masonry and rubble/field stone masonry construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1980-07-29	364	5.5	VII(18k)	0
1980-07-29	388	6.5	IX(11k)	100
1988-08-20	244	6.8	VIII(12k)	1k

Recent earthquakes in this area have caused secondary hazards such as landslides and liquefaction that might have contributed to losses.

Selected City Exposure

from GeoNames.org

MMI	City	Population
VIII	**Kathmandu**	**1,442k**
VII	Bhaktapur	< 1k
VII	Patan	183k
VII	Kirtipur	45k
VII	Nagarkot	4k
VII	**Bharatpur**	**107k**
VI	**Pokhara**	**200k**
V	**Gorakhpur**	**674k**
V	**Muzaffarpur**	**333k**
V	**Patna**	**1,600k**
IV	Dhankuta	22k

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Event ID: us20002926

Fig. 3.26: Nepal OnePAGER Alert Example

On the shaking hazard front, domestically, some public/private sector utilities run in-house shaking aggregation and estimation systems, including the East Bay Metropolitan Utility District (EBMUD's Marconi system) and Pacific Gas and Electric (PG&E).

Impressive systems also exist in Japan, Taiwan, New Zealand, Turkey, among other countries.

- JMA
- GNS
- INGV

On the rapid loss estimation front, several systems are in place in the U.S.

Internationally, *Erdik et al. (2011)* and *Erdik et al. (2014)* provide examples of operative rapid earthquake loss estimation systems.

- Taiwan Earthquake Rapid Reporting System,
- Realtime Earthquake Assessment Disaster System in Yokohama
- Real Time Earthquake Disaster Mitigation System of the Tokyo Gas Co.
- IGDAS Earthquake Protection System
- Istanbul Earthquake Rapid Response System
- ELER
- SELENA
- OpenQuake (OQ, GEM Foundation)
- GDACS
- QuakeLoss (WAPMERR)
- PAGER (USGS)

Note: Links and pointers to non-USGS sites are provided for information only and do not constitute endorsement by the USGS (see USGS policy and disclaimers).

Lastly, many systems are available and in operation in the U.S. for aggregating hazard and impact information for emergency response and awareness. Many are multihazard oriented, and only those with focus on earthquake information are mentioned here. Some examples include:

- InLet (ImageCat,Inc.)
- HAZUS-MH,
- ArcGIS online

As summarized by *Gomberg and Jokobitz (2013)*: "others have built in-house systems to organize, share and display observations using commercial applications like Microsoft's Streets and Trips and SharePoint, Google's GoogleEarth, or ESRI's ArcGIS. WebEOC, a real-time Web-enabled crisis information management system developed commercially by Esri, is meant to be an official link among public sector emergency managers in Washington State (see http://www.esi911.com/esi). While used by many agencies, it always was just one of multiple communication tools. A commonly expressed desire was for a centralized hub for all types of disaster information (like the Department of Homeland Security's Virtual USA)."

Further information on private sector tools can be found in the Department of Homeland Security (DHS) summary for the Capstone 2014 National Level (scenario) Exercise.

3.6 Disclaimers

3.6.1 General Disclaimer

Warning: Some USGS information accessed through this page may be preliminary in nature and presented prior to final review and approval by the Director of the USGS. This information is provided with the understanding that it is not guaranteed to be correct or complete, and conclusions drawn from such information are the sole responsibility of the user. In addition, ShakeMaps are automatic, computer-generated maps and have not necessarily been checked by human oversight, so they may contain errors. Further, the input data is raw and unchecked, and may contain errors.

- Contours can be misleading, since data gaps may exist. Caution should be used in deciding which features in the contour patterns are required by the data. Ground motions and intensities can vary greatly over small distances, so these maps are only approximate.
- Locations within the same intensity area will not necessarily experience the same level of damage, since damage depends heavily on the type of structure, the nature of the construction, and the details of the ground motion at that site. For these reasons, more or less damage than described in the intensity scale may occur. The ground motion levels and descriptions associated with each intensity value are based on recent damaging earthquakes. There may be revisions in these parameters as more data become available or due to further improvements in methodologies.
- Large earthquakes can generate very long-period ground motions that can cause damage at great distances from the epicenter; although the intensity estimated from the ground motions may be small, significant effects to large structures (e.g., bridges, tall buildings, storage tanks) may be notable.
- The utilization of DYFI data on ShakeMap, in addition to using recorded peak ground motions, is standard-operating-procedure for some ShakeMap operations, including the Global ShakeMap (GSM) system operated out of the USGS NEIC. The algorithmic strategy for including these data in ShakeMap is documented in the Technical Guide. As described by Wald et al. (2011), the ultimate discretion to use, filter, or overrule specific internet-based or historic intensities (or specific suspect strong motion data, for that matter) remains with the ShakeMap operators. A number of filtering and quality control strategies are in place (e.g., Wald et al., 2011), but erroneous or suspect data can not always be culled immediately. While we make efforts to provide consistent quality control of the data, the DYFI system depends upon open, citizen-science based input from the public. A number of studies have shown these data to be generally reliable, but the data reliability may vary from event to event. Moreover, macroseismic intensities are fundamentally non-unique: Differing polygonal aggregations for computing Community Decimal Intensities (CDI, using geocoded boxes or ZIP codes, for example, Wald et al., 2011) may yield varying intensity values at specific locations. [Historic or modern MMI or EMS-98 intensity assignments are also non-unique; the assignment can vary from expert to expert, the selection of areas may vary, and occasionally different structure types may indicated alternative intensities]. Changes to the size of the areas used to aggregate CDIs often trade off a greater number of responses per polygon (hence greater confidence in the derived intensity) against a more precise spatial location. DYFI data are routinely used on the GSM systems and other regional ShakeMap systems of the ANSS. DYFI data are not currently (as of 2016) used in the Northern or Southern California ShakeMap systems, in part due to the adequacy of strong-motion station coverage there.

3.6.2 ShakeMap Update Policy

Warning: ShakeMaps are preliminary in nature and will be updated as data arrives from a variety of distributed sources. Our practice is to improve the maps as soon as possible, but there are factors beyond our control that can result in delayed updates.

- For regions around the world, where there are insufficient near–real-time strong-motion seismic stations to generate an adequate strong-ground-motion data-controlled ShakeMap, we can still provide a very useful estimate of the shaking distribution using the ShakeMap software. Site amplification is approximated from a relationship developed between topographic gradient and shear-wave velocity. Additional constraints for these predictive maps come primarily from additional earthquake source information, particularly fault rupture dimensions, observed macroseismic intensities (including via the USGS "Did You Feel It?" system), and observed strong ground motions, when and where available.
- There is no formal "final" version of any ShakeMap. Version Control is up to users. ShakeMap version numbers and timestamps are provided on the maps, webpages, grid files, and metadata.
- Our strategy is to update ShakeMaps as warranted from a scientific perspective. We reserve the option to update ShakeMaps as needed to add data or to improve scientific merit and/or presentation of the maps in any way beneficial. This most typical update is after new data arrive, finite-fault models get established or revised, magnitude gets revised, or as improved site amplification maps, ground motion prediction equations, or even interpolation or other procedures become available.

Recent ShakeMap update examples:

- For the very deadly 2008 Wenchuan, China, earthquake, the Chinese strong-motion data were not made available for several months.
- For the 2011 Tohoku, Japan earthquake, the magnitude was updated from 7.9 to 8.9 over the course of the first hour after origin time. The Japanese strong-motion data processing center was impacted by the earthquake, yet they provided data for nearly a thousand seismic stations within several days after the earthquake. These vital data were added to the ShakeMap as soon as they became available.
- Due to telemetry limitations, some important seismic station data for the 2014 American Canyon, California, earthquake came in minutes, hours, and as late as four days after the event. The data were added to the ShakeMap soon after they were received and processed. The magnitude also changed from an initial M5.7 to M6.0, and this, too, affected the ShakeMap. Lastly, the causative fault location was added by the Northern California ShakeMap operators several days after the earthquake.

Updates to Online Maps

- **Real-time ShakeMap Updates**. Changes can be tracked with the ShakeMap version numbers and timestamps found in the metadata, the *info.xml* and *grid.xml* files, and on the maps themselves (time generated). The *info.xml* file contains timestamps, number of stations used, GMPE information, and many other attributes that could have changed from version to version. Often a text statement is provided that notes significant changes for a particular version.
- **ShakeMap Atlas Updates**. The ShakeMap Atlas uses version numbers for each Atlas event; the overall Atlas collections is also Versioned. Currently ShakeMap Atlas Version 2.0 is online in the ComCat database, and the older Atlas (Version 1.0) can be found online on the legacy ShakeMap Archives pages.
- **Scenario Revisions**. ShakeMap Scenario collections uses version numbers for each event; the overall scenario collections is named according to their source. Currently ShakeMap Atlas Version 2.0 is online in the USGS Comprehensive Catalogue (ComCat) Earthquake database. Some older scenarios are online on the legacy ShakeMap Archives pages. Scenario ShakeMaps will be revised when the underlying probabilistic seismic map fault segmentation or other particulars (like GMPE selection) change. Older versions will be archived in ComCat.

CHAPTER

FOUR

SOFTWARE & IMPLEMENTATION GUIDE

Installing and operating a ShakeMap system is a non-trivial endeavor. While the software can be easily obtained, and installed and configured with a few hours work, there are a great many issues that need to be addressed when an organization considers deploying a ShakeMap system. In this section, we will discuss a number of these issues.

4.1 Implementation Considerations

4.1.1 Seismic Network

The single most important prerequisite for operating a ShakeMap system is the existence of a seismic network capable of determining the location and magnitude of significant earthquakes within minutes of their occurrence. This network must also produce parametric data for ShakeMap within minutes of the earthquake. The parametric data should come from free-field strong motion sensors with real-time or near–real-time telemetry, and minimally consist of the horizontal components of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV), as well as (ideally) 5% damped pseudo- spectral acceleration (PSA) at 0.3, 1.0, and 3.0 sec periods.

In the absence of such a network, there is little reason to operate ShakeMap locally. The USGS operates a ShakeMap system that produces maps for significant global earthquakes within a few minutes of their occurrence, and incorporates any available data from the Global Seismic Network (GSN), "Did You Feel It?" (DYFI), and any other parametric data to which we have access. These maps are immediately delivered to the PAGER system and ShakeCast. It would be far simpler in many cases to obtain the ShakeMap products from the USGS (through the website or ShakeCast) and use them for local or regional response and recovery efforts, perhaps even hosting them on local servers, than to attempt to duplicate our existing system.

Even where a seismic network is operational, it may be preferable to work with the USGS to produce ShakeMaps. As the following sections will illustrate, running a ShakeMap system is a considerable operational undertaking, and in many instances it will strain the resources of local or regional networks. The USGS operates a fully-staffed, 24/7 operations center for global earthquakes and produces ShakeMaps on a daily basis. If a regional network's parametric data can be made available to the USGS, the USGS's global ShakeMap system will include that data in the processing, and finished ShakeMap products can be delivered via ShakeCast for local consumption. Please contact us if you are interested in this kind of arrangement.

4.1.2 Seismic Stations and Parametric Data

As mentioned above, seismic waveform or parametric data must be communicated to the processing center in real-time or near—real–time. The sensors must be "free field" (i.e., not located in, or adjacent to, large structures) and installed in accordance with modern standard practices. Strong-motion instruments are preferred for ShakeMap, as broadband instruments typically clip when ground motions reach the level of interest to ShakeMap. Co-located strong-motion and broadband instruments can, however, increase the dynamic range of a station and its overall usefulness, but the network operator is responsible for specifying the crossover from broadband to strong motion, and ShakeMap should be presented only with the amplitudes from the favored instrument. Off-scale, clipped, below-noise, or otherwise unreliable data must be flagged or omitted from the ShakeMap input files. Horizontal components are mandatory—ShakeMap does not use vertical components.

At a minimum, the network must produce PGA and PGV for the ShakeMap stations, but PSA (at 0.3, 1.0, and 3.0 sec) is also desirable. The algorithms used to compute the parametric data should be verified against known standards. ShakeMap can be quite helpful in highlighting grossly mis-calibrated stations, but it is best to find these (and more subtle) errors before a large earthquake strikes.

Intensity data from the USGS's DYFI system (or an equivalent regional internet intensity system) is acceptable as input to ShakeMap; however, care should be exercised with international DYFI data, as it is often aggregated by city and therefore may be too coarse-grained for large-scale maps.

4.1.3 Triggering ShakeMap

The operator must give careful consideration to the way ShakeMap will be triggered. Unless an operator is constantly standing by to run ShakeMap, the system must be automatic to be useful. The operator must select the boundaries of the region ShakeMap will cover and the minimum earthquake magnitude that will trigger a run. These choices will be influenced by the reliability of the network's earthquake location and magnitude data over the region in question. The operator must also consider that a large earthquake may occur outside their region of responsibility, but have effects inside their region.

The ShakeMap software is distributed with a program for responding to event triggers and queuing events to be processed, but it is only applicable to the AQMS network software. While this software can serve as a guide, users of other systems (e.g., Antelope, Earthworm) will need to develop their own triggering systems.

Once triggered, ShakeMap will expect to find event and parametric data files in the event's input directory. Whether the amplitudes are retrieved from a database or stored in files, it is the operator's responsibility to provide ShakeMap with properly formatted files. Again, example programs are distributed with ShakeMap, but operators should anticipate that some coding may be necessary.

4.1.4 System Configuration

While it is relatively easy to install and run the ShakeMap software, a great deal of consideration is needed to properly configure the system for a particular region. ShakeMap presents the operator with a large number of configuration options, and these options will directly affect the accuracy and reliability of the products. The operator must select the proper GMPE or GMPEs for the region, and specify under which conditions they will be used. An appropriate Ground-Motion–Intensity Conversion Equation (GMICE) must likewise be chosen. The operator may also elect to use an Intensity Prediction Equation (IPE) or to use the default virtual IPE. For best results, the operator will need to provide a Vs30 grid, and while the USGS's Vs30 server can supply such a grid based on topographic slope, a grid based on regional geology is preferable [1]. The user must also decide whether to use GMPE-native or Borcherdt-style site correction factors. This is just a partial list of configuration choices. There are numerous other configurable parameters, all of which must be carefully chosen.

While the default ShakeMap webpages are configurable, they are fairly rudimentary and outdated. In addition, the webpages and ShakeMap products are all in English. Operators wishing more sophisticated webpages or non-English support can anticipate a substantial investment in bringing the system online. Some modifications of the ShakeMap software may be required for languages other than English, but such modifications may make it more difficult to update the software.

For further information on ShakeMap configuration, see the *Software Guide* and the ShakeMap configuration files themselves.

[1] The VS30 server currently provides GMT *grd* files in pixel node registration and ShakeMap works in gridline node registration. You can fix your Vs30 file by:
grdsample your_vs30_grid.grd -Gnew_file_name.grd –T
You then configure *grind.conf* to look at *new_file_name.grd*. See *grind.conf* for details.

4.1.5 Operations

Once an organization begins producing and distributing ShakeMaps, end users will begin to depend upon them and develop systems that incorporate ShakeMap products into their response and recovery operations. This means that it essentially becomes mandatory to produce ShakeMaps following significant earthquakes, and failure to do so is extremely conspicuous. A robust ShakeMap operation requires the 24/7 availability of operational personnel. If the facility is not continuously manned, on-call staff must be designated, and those staff must have the ability to access and operate the ShakeMap system remotely. Significant earthquakes almost always require some manual intervention (changing map scale, re-centering, addition of finite fault, inclusion/exclusion of data, etc.), and experienced personnel are required to evaluate the situation and perform the necessary tasks.

There are additional, more routine, operational considerations. An experienced seismologist should routinely review all of the ShakeMaps produced by the system and take action to correct any deficiencies. A network seismologist should also review the inputs and outputs of ShakeMap to insure that all stations are producing appropriate data. A ShakeMap operator should routinely review all ShakeMap processes, logs, databases, and outputs to insure the system is operating as expected.

The ShakeMap software is usually updated a few times a year. These updates contain important bug fixes, new functionality, new products, and general improvements. An operator must review the change logs, decide when to apply the updates, and test the updated software before it is put into production mode. Occasionally it may be desirable to rerun earlier events or scenarios to take advantage of the capabilities of the new code.

Hardware and software systems will need to be monitored and maintained for around-the- clock availability. This includes not just the seismic network and ShakeMap systems, but also web servers and other network hardware and software required for delivering products to end users. The personnel responsible for these systems must be on-call and able to access the necessary systems remotely. Automatic monitoring of mission-critical hardware and software is strongly encouraged. These systems should also have several hours of backup power in case of an outage. Periodic outage tests should be conducted to ensure that all necessary systems remain operational.

As mentioned above, users can be expected to make use of ShakeMaps in a variety of ways. However, many organizations that could make use of ShakeMap products are unaware of ShakeMap and the ways it could serve their earthquake response and recovery needs. We have found that a sustained outreach effort is necessary to maximize the adoption of ShakeMap and, thus, its value to society. Potential end users include public utilities, government and private transportation companies, police and fire departments, regional and national emergency response organizations, private companies with distributed facilities (e.g., banks, chain stores, telecoms), insurance companies, investment houses, and many others. Not only can ShakeMap-improved response efforts benefit post-earthquake recovery, these organizations can provide much-needed support for network and ShakeMap operations. It is highly recommended that regional networks considering the implementation of ShakeMap develop a detailed outreach plan.

4.1.6 Scenarios

One important use of ShakeMap is the generation of earthquake scenarios. Scenarios are predictive maps of the potential shaking resulting from hypothetical future (or past) earthquakes. Scenarios can be used for planning exercises, public information, or research. Some users may request specific scenarios, but it is generally worthwhile to develop a suite of scenarios to cover the likely earthquake hazards of a region. At the USGS, we have begun using disaggregated hazard maps as the basis for our nationwide scenario project. In other words, we separate out the individual earthquakes (and causative faults) that together comprise the hazard in a probabilistic hazard map. The disaggregated maps represent the best scientific consensus of the probable earthquakes in a region, and should be sufficient for most uses. Requests for custom scenarios should be carefully evaluated. The earthquakes represented should be credible in terms of both the causative fault and the magnitude. In most cases, one of the disaggregated hazard scenarios should suffice.

4.1.7 Backup

Because of the importance of ShakeMap, it is advisable to run redundant systems. Most ShakeMap operations have a primary and backup machine. The backup machine runs events as if it were the primary, except it does not transfer its products to the web or other destinations. If the primary server fails, the backup can be switched over to primary merely by changing the transfer configuration. This arrangement is also useful when software updates are available. The update can be applied and tested on the backup system. Once it is deemed to be operating correctly, it can be made primary, and the primary server can be updated.

Since most seismic networks are operated from earthquake-prone regions, there is also the potential that the entire facility will be taken offline. For this reason, it is desirable to have a backup system operating in a remote location, preferably many kilometers away.

As we have mentioned elsewhere, the USGS makes ShakeMaps for global earthquakes and provides backup to U.S. regional networks. If you would like to discuss remote backup for your ShakeMap system, please contact us.

4.2 ShakeMap Implementation Checklist

The checklist below is based on the one we use when discussing ShakeMap operations with active or potential producers within the USGS's Advanced National Seismic System (ANSS). While some of the issues are ANSS-specific, there may be analogous considerations for other regional or national networks.

1. **Triggering**
   (a) Automatic Triggering System. How is ShakeMap triggered and how does it access or receive parametric data? How is robustness of this approach achieved?
   (b) Location & Magnitude Reliability. Are there limitations to location and magnitude determination by the regional network that would adversely affect automatic ShakeMap products?
   (c) Regional Coverage. What are the boundaries of the area within which the local network will generate ShakeMaps?
   (d) Alarm Region. For events outside ShakeMap boundaries, is a ShakeMap run initiated? Under what conditions?
   (e) ShakeMap ID. Does the naming of ShakeMap ID follow the ANSS convention? If not, can they be easily associated with the authoritative ID?
2. **Station Coverage and Parametric Data**
   (a) Real-time or near–real-time data flow. What are the types and distribution of stations contributing to ShakeMap? Are all stations "ShakeMap-quality"?
   (b) Parametric Data. How are the parametric data computed? (Five parameters: PGA, PGV, and three periods of PSA.)
   (c) Are parametric data imported from other sources (NSMP-triggered stations, state or commercial agencies, neighboring networks, etc.)? How are these integrated with the ShakeMap input?
   (d) Are "Did You Feel It?" data used as input?
   (e) Co-location of different sensor types, priorities, and preventing redundant input data. How are co-located instruments resolved by the network to produce only a single (best) set of amplitudes for ShakeMap?
3. **System Specifications**
   (a) Grind parameters. Review the parameters in *grind.conf*. How were they determined?
      i. GMPEs. Which Ground-Motion Prediction Equations are used, and under what conditions?

ii. IPEs. Which Intensity Prediction Equations are used, and under what circumstances?

iii. GMICEs. Which Ground-Motion–Intensity Conversion Equations are used?

iv. Site Amplification. How are site conditions established and what amplifications are used (GMPE-native, Borcherdt-style)?

v. Other parameters. Grid spacing, map area, outlier levels, bias parameters. Have all parameters been evaluated for optimal performance?

vi. *Shake.conf*. When is map size increased, PSA and HAZUS output produced, etc.?

(b) Spatial Correlation Function. Which spatial correlation function is used?

(c) Basin response. Is a basin response applied in any areas? If so, how was the basin depth file produced, and are predicted ground motions consistent with reality?

4. **Operations**

(a) Which version of ShakeMap is operational? Who is responsible for updating the software when updates are released? When and how are the updates performed?

(b) Who is responsible for routine scientific review of ShakeMaps produced by the network? Do these people receive alarms when ShakeMaps are produced?

(c) Who is responsible for routine operational review of the ShakeMap system (checking logs, process and database monitoring, etc.)? When are reviews performed?

(d) Reprocessing. Under what circumstances are events reprocessed (new data, change in source parameters, etc.)? What about in the longer term (ShakeMap software updates, changes in operational parameters)?

(e) Finite faults. For larger earthquakes, who is responsible for producing a finite fault model for inclusion in ShakeMap? What procedures are in place for assuring this is done?

(f) Aftershock exclusion. How will you change the triggering threshold immediately after a major earthquake in your region?

(g) Version history. Under what circumstances are maps (and their input data) preserved using ShakeMap versioning?

(h) Have there been any local changes to the ShakeMap software that will hinder upgrades? Can these customizations be incorporated into the ShakeMap distribution for easier upgrades? If not, how can they be structured to accommodate easy upgrades of ShakeMap?

(i) What is the hardware for ShakeMap processing and for local web service?

(j) How is hardware redundancy achieved?

(k) Are the hardware and software systems automatically monitored? Do they generate alerts when problems are detected?

5. **Product Distribution and Uniformity**

(a) Are products delivered to Earthquake Program Web Servers via PDL?

(b) Are local webpages produced? Where do they reside? How is ShakeMap transferred? Are redundant web servers and 24/7 support available?

(c) Are regional ShakeMap webpages customized to reflect regional configurations and implementation specifics?

6. **ANSS Coordination**

(a) Provide Software/Feedback to ANSS. To benefit current operators and to ensure compatibility and ease of installing new ShakeMap software releases, changes to ShakeMap software (above and beyond configuration changes) should be provided to Bruce Worden for review, standardization, and inclusion in new releases.

(b) Provide contacts, their background, and roles in implementation, coordination, and operations.

(c) Are all responsible parties subscribed to the *shake-dev* mailing list?

7. User Coordination: List significant users and outline any outreach efforts or plans. It is very useful to have a feeling for which users will rely on ShakeMap in each region, as well as to coordinate efforts for users of ShakeMaps for multiple regions (e.g., FEMA, DHS, Military).

8. **Scenarios and Archives**

   (a) Scenario earthquakes should be made to be consistent with USGS National Hazard Maps, both with attenuation relations and in source parameterization. Coordination with the National Earthquake Information Center (NEIC) is essential.

   (b) Is a copy of scenarios also available on the USGS web site?

   (c) How and when will scenarios be reprocessed?

   (d) Archive "final" ShakeMaps for significant events. Many users want ShakeMaps for significant events "frozen in time". Once a ShakeMap gets used as a reference for damage-loss modelers, insurance investigators, and researchers, there needs to be an archival version of these events. Once all the available ground-motion data have been collected and included in ShakeMap, that Version of the map needs to be kept available even if additional updates are made. (This process has not yet been fully vetted.)

9. **Backup Strategy**

   (a) If the primary system fails, what provisions exist for a backup system or another network to take over ShakeMap operations? Is this backup automatic or manual?

   (b) If the entire facility goes offline, is there an off-site backup?

   (c) Are waveform or parametric data transmitted to NEIC for national-level backup?

10. **Feedback**: Do you have any recommendations for further support, software, features, etc.?

4.3 Software Availability & Software Guide

ShakeMap requires the freely available PERL, MySQL, and GMT (Generic Mapping Tools), as well as a few other packages. PERL and GMT are used quite extensively, so any background with them is advantageous. You will need to assemble the basic GMT-formatted basemaps, road, city data files, etc., but such data may already be available for your area.

The ShakeMap software is freely available, open-source, and distributed under a Public Domain License. It runs on Solaris, FreeBSD, Mac OS X, (U)nix, and numerous versions of Linux (including Red Hat and Debian). It does not run on Windows. See the Software Guide for more information. The software is available as a SubVersion checkout from:

https://vault.gps.caltech.edu/repos/products/shakemap/tags/release-3.5/

Note: Do not attempt to install ShakeMap on Ubuntu Linux. It has been nothing but a problem for everyone who has tried it, and we will no longer provide support for this operating system.

The Software Guide included in the *doc* directory of the distribution will always be the most up-to-date and should be consulted when installing and configuring ShakeMap. The Software Guide may also be obtained by download. This version of Guide is not guaranteed to be the most up-to-date, however. It should be used only to familiarize oneself with the general requirements of installing and operating ShakeMap. When installing the software, the Guide in the *doc* directory of the software distribution should be followed.

We strongly recommend that ShakeMap operators and users sign up for the *shake-dev* mailing list:

https://geohazards.usgs.gov/mailman/listinfo/shake-dev

We use this mailing list to communicate software updates, as well as provide support when users have problems, suggestions, etc.

CHAPTER

FIVE

REGIONAL OPERATIONS

Note: This section will be updated with Regional ShakeMap specifications after input from the ANSS Regional Seismic Networks operators.

As described in the section on real-time ShakeMap archives, ShakeMaps are generated via independent systems running at ANSS Regional Seismic Systems (RSNs) in Northern California, Southern California, the Pacific Northwest, Utah, Nevada, and Alaska. For the rest of the U.S., the ShakeMap group at the USGS National Earthquake Information Center (NEIC) produces maps for the regional networks operating in Hawaii, New England, and the Central and Eastern U.S. on a system referred to as Global ShakeMap (GSM). The input, metadata, and output files produced by all these instances are aggregated by the USGS via the Earthquake Hazards Program web system. GSM also provides backup capabilities for the RSNs, but with degraded capabilities; not all data are flowing from the RSNs to GSM automatically.

Separate independent systems running in Puerto Rico and New England generate ShakeMaps, but these instances do not deliver them through the USGS Earthquake Hazards Program webpages (at the time of this writing). GSM covers these regions, but does not yet access the full set of data available to these regional systems.

In this section, we describe customizations employed by ShakeMap systems running throughout the Advanced National Seismic System (ANSS) regions nationwide as well as the Global ShakeMap (GSM) system running at the NEIC in Golden, Colorado.

Note: Specifications of input parameters, data, and other configurations used for any ShakeMap can be found in the event-specific summary files (*info.xml*).

Details for about regional configurations for ShakeMap operators can be found in the *Software & Implementation Guide*. For contact information for ANSS regional operators see the *Acknowledgments*.

- **Northern California**
- **Southern California**
- **Pacific Northwest**
- **Intermountain West**
- **Mid-America**
- **Northeast**
- **Alaska**
- **Puerto Rico**
- **Hawaii**

- *Coverage Area*. State of Hawaii (Bounds:)
- *Operations*. ShakeMap operated at NEIC in conjunction with HVO RSN operators
- *Triggering and Data Flow*.
- *Site Condition Map*. Vs30 from topographic slope-based (*Allen and Wald, 2009b)*
- *Ground Motion Prediction and Conversion Equations (GMPE/IPE/GMICE)*.
- *Other Local Characteristics*.

CHAPTER

SIX

FUTURE DIRECTIONS

ShakeMap is a continual work-in-progress. We note several ongoing developments and "To-Do" lists. Please make suggestions if you would like to weigh in.

6.1 Research & Development

Feature Requests:

- Add NGA-West2, NGA-East, and NGA-Subduction GMPEs, including basin terms for NGA-West 2 GMPEs.
- Improved and additional site amplification approaches and tables, in addition to native GMPE (Vs30) site corrections (e.g., *Seyhan and Stewart, 2014*).
- R&D to improve PGV-to-MMI conversion for large-magnitude and high-velocity ranges. May require switch to converting long-period spectral acceleration to MMI. Simulated ground motion time histories may be useful to augment sparse data at high PGV/MMI.
- Consideration of vector-component IMs, static displacements, and duration-based IMs (Arias Intensity; Cumulative Average Velocity, or CAV) [1]

In Progress:

- Spatial variability. Implement optimization methods to compute the spatial correlation field for ShakeMap using successive conditional simulations (Verros et al., 2016). Deliver ShakeMap scenarios with multiple realizations of variability.
- Directivity. Update Rowshandel (2010) model and implement selected NGA-West2 models.
- Landslide and liquefaction likelihood grid (*sechaz.grid.xml*). Computing probability and distribution of landsliding and liquefaction per ShakeMap grid cell. Delivery via Product Distribution Layer (PDL) for ShakeCast, PAGER, and open access.
- Scenario update for all U.S. regions. Delivery to ComCat/Web and allow users a variety of search capabilities (site- or fault-specific).
- Interactive (dynamic) webpages plots (regression, bias, outliers, station amplitudes).
- Improved content and rendering of ShakeMap metadata (*info.xml*; see *Thompson et al., 2016*).

[1] We are continuously considering the use of additional ground-motion parameters (IMs) for ShakeMap. However, any such additions cannot be made lightly. In part, this is due to the fact that this requires upgrading process seismic network processing streams that produce parametric and these processes vary significantly among ANSS data sources.

6.2 Software: ShakeMap 4.0 (Python)

The release of ShakeMap version 4.0 will represent a significant departure from previous versions. All of the important computational modules have been refactored into the Python programming language and make use of the tools in the widely available Python "scientific distribution". The core ShakeMap code, approaching fifteen years old, was due for a major overhaul—to more organically incorporate the many extensions that had been added over its lifetime, and to facilitate several new demands from ShakeMap software and ShakeMap's expanded role as a global provider of post-earthquake information, earthquake scenarios, and inputs for loss-modeling software.

One of the advantages of the rewrite of ShakeMap into the Python language was the availability of the GEM OpenQuake (OQ) library of Ground Motion Prediction Equations (GMPEs). The OQ hazard library provided us with a broad range of well-tested, high-performance, open-source GMPEs. Due to constraints imposed by the software architecture of earlier implementations of ShakeMap, the development of GMPE modules was time-consuming and difficult, which restricted the number and timeliness of the available modules. The OQ library provides a broad array of current GMPE modules, as well as a framework for easily adding new modules (whether by GEM or ShakeMap staff), jumpstarting our efforts to re-implement ShakeMap.

The OQ hazard library also provides supporting functions for using the GMPE modules, including a set of software classes for computing the various distance measures required by the GMPEs. The ShakeMap fault model, however, was somewhat more general than allowed for by the OQ planar surface modules, so we sub-classed the OQ "surface" class and implemented our own fault module. The open-source, cooperative nature of the OQ project allowed us to contribute our new module back to the OQ repository, and thus make it available to other users.

In addition to making use of the GEM OQ library, there are a number of other advantages to using Python for an application like ShakeMap. The dynamic nature of the language means that development time is much reduced, allowing a small team to generate useful code in a short amount of time. Also, there is an active scientific computing Python community that has created many tools that solve common problems, including an array object for vectorized operations, input/output routines for common data formats, and plotting/mapping libraries. These tools further help to reduce development time and effort. [**Delivery Date: 2016**]

CHAPTER

SEVEN

ACKNOWLEDGMENTS

Many contributions in a variety of forms have greatly helped in the development, implementation, and use of ShakeMap. ShakeMap is just one end product of a very sophisticated seismic network. Credit is given to all involved with the regional and national networks in the United States working under the auspices of the USGS Advanced National Seismic System (ANSS).

Much of the early conceptual development of ShakeMap benefitted greatly from discussions with Professors Kanamori and Heaton at Caltech. Both the TriNet Steering and Advisory Committees also provided ongoing oversight and feedback in the early years of TriNet. Discussions with many colleagues, including Woody Savage, Ken Campbell, Robert Nigbor, and Mark Petersen, provided additional guidance. Early trips to the Japanese Meteorological Agency (JMA), and in particular discussions with Keiji Doi, were also helpful.

Early ShakeMap webpages survived substantial traffic spikes due to the ingenuity and vigilance of Stan Schwarz (USGS, Pasadena). Many aesthetic improvements and integration of the ShakeMap webpages into the USGS Earthquake Hazards Team webpage standard templates were guided by Lisa Wald (USGS, Golden). Later implementations were greatly improved by the Haz-Dev Web Team, particularly by Jeremy Fee and Eric Martinez. They also provide the GeoJSON and other feeds needed for automatic ShakeMap downloads.

Craig Scrivner, then at the CA Department of Mines & Geology (CDMG), contributed greatly to the initial ShakeMap software development. Pete Lombard (U.C. Berkeley) contributed to several important aspects of ShakeMap code development and Q&A, including developing *plot_regr*.

ANSS National ShakeMap Coordinators:

- Bruce Worden: Synergetics Inc., Golden, Colorado, cbworden@usgs.gov
- David Wald: USGS, Golden, Colorado, wald@usgs.gov

Global ShakeMap (GSM) is run out of NEIC, Golden, CO, and is operated primarily by Kuo-Wan Lin, Kristin Marano, Vince Quitoriano, Eric Thompson, David Wald, and Bruce Worden.

At regional network centers, Kris Pankow (University of Utah), Steve Malone (University of Washington), Kuo-Wan Lin (formerly CGS, now USGS, Golden), Doug Dreger, Pete Lombard (U.C. Berkeley), and Lind Gee (USGS, Menlo Park), Egill Hauksson (Caltech), Glen Biasi (Univ Nevada, Reno), and Howard Bundock (ret.), Tim MacDonald, David Oppenheimer, and John Boatwright (USGS, Menlo Park) all played a critical role in testing, providing feedback, and improving the ShakeMap system. In addition, a number of other people assisted the above colleagues in the regional ShakeMap implementation and operation.

ShakeMap ANSS Regional Coordinators	
Southern California:	Robert Graves, rgraves@caltech.edu
	Gary Gann, agann@usgs.gov
Northern California:	John Boatwright, boat@usgs.gov
	Peggy Hellweg, peggy@seismo.berkeley.edu
	Tim MacDonald, tmacdonald@usgs.gov
	Pete Lombard, lombard@seismo.berkeley.edu
Utah:	Kris Pankow, pankow@seis.utah.edu
Alaska:	Natalia Ruppert, natasha@gi.alaska.edu
	Matt Gardine, mgardin2@alaska.edu
Pacific Northwest:	Paul Bodin, bodin@uw.edu
	Renate Hartog, jrhartog@uw.edu
Nevada:	Ken Smith, ken@seismo.unr.edu
	Gabe Plank, gabe@seismo.unr.edu
Puerto Rico:	Victor Huerfano, victor@prsn.uprm.edu

We received extremely important feedback regarding the user interface from participants through a number of meetings and workshops in CA for scientific and engineering perspectives, as well as for a very wide variety of users' perspectives. These workshops were organized by Jim Goltz and Margaret Vinci. In addition, ongoing feedback has always been abundant and provides critical advice and ideas that seeds ongoing, iterative improvements to the ShakeMap system.

Over the years, numerous student researchers contributed greatly to the operation, development, user support and many other aspects of ShakeMap, particularly developing the ShakeMap Atlas. The students include undergraduates Chloe Gustafson, Paul Geimer, Alicia Hotovec, Kendra Johnson, Rebecca Johnson, Russell Mah, Tanya Slota; graduate students Lily Seidman, Sarah Verros, Leslie McWhirter; and post-doctoral fellows Trevor Allen and Daniel Garcia.

International collaborators include Alberto Michelini, and Licia Faenza (INGV, Rome) and Carlo Cauzzi (ETH Zurich). ShakeMap Workshops help at U.C. Berkeley and at the Erice, Sicily Summer School were very helpful in improving ShakeMap implementations around the country and around the world.

Doug Bausch (formerly FEMA) played a vital role in standardizing HAZUS loss estimates using ShakeMap input, responding to numerous national earthquake responses, and promoting the use of ShakeMap among the earthquake response and planning communities. In interfacing with HAZUS software and loss estimates, contributions from Jahar Bouabid at Durham Technology, and Charlie Kircher of Charlie Kircher Assoc. were key.

USGS colleagues Vince Quitoriano and Kuo-Wan Lin have long operated, supported, and greatly added to the development of ShakeMap. Mike Hearne and Kristin Marano of the PAGER team have also provided support for ShakeMap. Eric Thompson has contributed greatly to the development of scenarios and advancing ShakeMap science. Kishor Jaiswal, Ned Field, Nico Luco, Mark Petersen have all been very helpful in software calibration and validation and overall advice.

Eric Thompson (USGS, Golden) and Emmette Wald provided helpful rewivews of this Manual.

Lastly, we are also extremely grateful for the recognition of the importance of ShakeMap and the ongoing internal and external support for its development at all levels within the USGS. Along the way, the support of John Filson, David Applegate, Bill Leith, Harley Benz, Cecily Wolfe, Woody Savage, Jill McCarthy, and many others has been critical.

ShakeMap relies extensively on the Generic Mapping Tools (*Wessel and Smith, 1995*).

Thank you all.

Bruce Worden & David Wald, December 2015

CHAPTER

EIGHT

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CHAPTER

NINE

GLOSSARY

Abbreviations, acronyms, and initialisms used in this report

ANSS Advanced National Seismic System: A USGS initiative to provide seismic monitoring for at-risk regions of the United States

California EMA The California Emergency Management Agency (formerly the California Office of Emergency Services)

DYFI Did You Feel It?

EHP USGS Earthquake Hazard Program

ENS Earthquake Notification System: earthquake notifications via text/email from USGS's Earthquake Hazard Program

FEMA Federal Emergency Management Agency: part of the U.S. Department of Homeland Security

GIS Geographic Information System

GMICE Ground-Motion–Intensity Conversion Equation

GMPE Ground-Motion Prediction Equation

GSM Global ShakeMap

HAZUS HAZards US: a loss-estimation program developed by FEMA

IM Intensity Measure: often used as a generic reference to Peak Ground Motions

IPE Intensity Prediction Equation

ISO International Standards Organization

MMI Modified Mercalli Intensity

NEIC the National Earthquake Information Center; part of the USGS, located in Golden, Colorado

PAGER Prompt Assessment of Global Earthquakes for Response

PGA Peak Ground Acceleration

PGM Peak Ground Motion: a generic term for PGA and PGV

PGV Peak Ground Velocity

USGS the United States Geological Survey, a bureau of the U.S. Department of the Interior.